Guidehouse
INSIGHTS

White Paper

Smart City Infrastructure for Automated Vehicles

Enhancing Driverless Situational Awareness with Offboard Sensing

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Executive Summary

Automated vehicles (AVs) are inching closer to larger scale deployments each year as the sensing, software, and compute capabilities continue to improve. However, although sensors have steadily increased in capability and costs have declined, they still have an important constraint—they are limited to line of sight. Human drivers have the same limitation, but the way computers process information still differs substantially from human cognition. To achieve the maximum possible safety benefits from automated driving systems (ADSs), it may be necessary to move beyond replicating and optimizing the human experience.

Municipalities around the world are piloting a wide range of smart city efforts, most of which include installation of sensors on local infrastructure. These sensors can provide useful insights to local planners and traffic management systems; the data can also be put to use by drivers whether they are human or software defined.

Cities, automakers, V2X technology suppliers, and parking operators should continue to work together to increase the effectiveness and deployment of this technology to not only improve the safety of AVs but also provide significant environmental and economic benefits.

Smart city sensing infrastructure combined with increasingly ubiquitous wireless communications and network edge computing can be used to provide offboard sensing capability to AVs. Through beyond line-of-sight sensing and perception, AV control can be optimized for proactive decision-making for smarter, dynamic routing and safer operation. It also provides an additional layer of redundancy and diversity for fail operational capability.

Successful deployments of smart city infrastructure to support AVs have been demonstrated in several notable projects globally. AVs such as robotaxis and shuttle buses have been provided with extended hazard warnings/perception by roadside units (RSUs) to augment their onboard sensors providing warnings about hazards posed by other vehicles and pedestrians and cyclists at complex intersections. Additionally, information to support traffic management and enforcement has been demonstrated. Automated valet parking (AVP) is another implementation of smart city infrastructure that has been proven. In this application, vehicles with minimal advanced driver assist system (ADAS) requirements are enabled to autonomously find and maneuver into parking spaces, demonstrating benefits of increased space efficiency of parking real estate, consumer convenience, and improved safety.

Collaborations are key to the successful development and rollout of smart city sensing infrastructure. Cities, automakers, vehicle to everything (V2X) technology suppliers, and parking operators should continue to work together to increase the effectiveness and deployment of this technology to not only improve the safety of AVs but also provide significant environmental and economic benefits.

On-Vehicle Sensing

The on-vehicle sensing systems are a core component of automated driving technologies, consisting of the sensors and compute platforms that enable the vehicle to understand the surrounding environment. The sensor suite commonly used in onboard perception systems can include cameras, light detection and ranging (lidar), radar, GPS, vehicle motion detection, and ultrasound.

Perceiving the Environment

Automated driving systems (ADSs) need to be able to pinpoint a vehicle's location and perceive its surroundings based on information primarily gathered from its onboard sensors. Sensing is the first stage of this operation, and a variety of sensors are chiefly employed to generate the raw data resulting from scanning the immediate environment, including cameras, lidar, and radar. The immediate position and velocity of the vehicle can be determined from an onboard GPS receiver, as well as motion detectors such as the vehicle's wheel speed monitor. Automated vehicles (AVs) are equipped with multiple sensor types to maximize the information available about the external environment and to ensure a degree of data redundancy. These multiple sensor inputs are merged using sensor fusion, which is undertaken by the ADS's compute platform.

To further support the localization of a vehicle, high definition (HD) maps are used to provide highly accurate information on the underlying geography and layout of the road network. These maps are made of multiple data layers that, in addition to the data offered by conventional maps, can provide information on traffic regulations and parking, as well as historic data for congestion levels and average traffic speeds.

Perception involves the real-time analysis of the sensor data to recognize and position the objects detected in the vehicle's immediate surroundings, whether they be other road users, pedestrians, or other obstacles. Furthermore, traffic information can be interpreted to understand road signs and lane markings to provide a deeper understanding of the surrounding road environment. The vehicle's compute platform carries out the processing to evaluate the sensor data and correctly classify detected objects and identify potential hazards.

Prediction, Path Planning, and Control

The data from sensing and analyzing the vehicle's environment is essential for the short-term prediction of events likely to occur on the surrounding road. The prediction of upcoming hazards for a few seconds in advance is a challenging step carried out by the vehicle's compute platform. The behavior of other road users and pedestrians is analyzed to identify upcoming hazards and to enable the path planning for the road ahead. Actions recognized by the ADS can signal imminent changes of behavior of other road users. For example, flashing indicators on other vehicles and leaning or micro changes in the direction of cyclists may signal a change of lane or direction. Also, the movement of pedestrians on a sidewalk approaching a curb could indicate that they are about to cross.

By predicting the trajectory of other road users, the ADS can identify potential hazards and determine the optimum positioning of the vehicle to progress on its route. Some systems may identify multiple potential paths, which are continually monitored depending on the real-time road conditions. Safety is the most important factor for path planning and certain ADS developers provide a further algorithm to validate the safety of the selected path. An example of these virtual safety guardrails is Mobileye's Responsibility-Sensitive Safety, which defines a set of rules to ensure safe decision-making by AVs, including situations involving interactions with other road users and emergency actions in the case of an unavoidable accident. NVIDIA has developed a similar system named Safety Force Field that defines a set of acceptable actions that ensure that unsafe situations do not arise or are not exacerbated.

Once the ADS has planned a safe path, the system can issue the commands to control the vehicle as planned. Control is the final phase of an ADS's operation and acts to command the vehicle to travel or maneuver in response to the calculations of the previous steps. Actuation systems enable the vehicle to maneuver through the environment based on what it is being perceived. These systems include acceleration, braking, and steering.

Line-of-Sight Limitations

Onboard vehicle perception can provide sensing better than human vision and enable fully autonomous vehicle operation. However, there are limitations to relying solely on these sensors. Light detection and ranging (lidar), radar, and cameras operate on a line-of-sight basis; therefore, their perspective can be obstructed by other vehicles, buildings near sharp bends or near curbs, and obstacles such as construction on the road blocking their view. These shortcomings in onboard sensor perception can result in a limited time to react to unexpected hazards in these scenarios.

Expanding Situational Awareness for AVs

Offboard sensors mounted by the roadside complement the perception provided by on-vehicle sensors and extend the situational awareness of highly automated vehicles. The information collected by these sensors enables vehicle to everything (V2X) communications, which includes vehicle to vehicle (V2V), vehicle to infrastructure (V2I), and vehicle to pedestrian (V2P). The perception from roadside units (RSUs) containing V2X sensors in addition to the information from the on-vehicle sensors permits the merging of multiple points of view, provides a greater degree of data redundancy, and facilitates better prediction of events and faster vehicle responses.

V2X systems enable connected vehicles to perceive what is beyond a bend in the road or what otherwise would be unseen at a blind intersection. Hazards detected by RSUs can be communicated to vehicles much earlier than would be detected by a vehicle alone, permitting ample time for a vehicle to take evasive action and to provide increased levels of safety. Moreover, V2X systems can relay traffic information to vehicles such as roadworks, accidents, and the approach of emergency vehicles. These sensors utilize similar technology as found on AVs, and can typically include one or more sensor types including lidar, radar, and cameras. Table 1 compares the key features of these sensors.

Table 1 Feature Comparison for V2X Sensor Technologies

Feature	Lidar	Camera	Low Resolution ADAS Radar
Minimum Number of Sensors Required	1	4	4
Relative Processing Power Required	Low	High—total fusion controller	Individual controller, total fusion controller
Relative Cost	$$$	$	$
Positional Accuracy	★★★	★☆☆	★★☆
Object Recognition	★★☆	★★★	★☆☆
Traffic Recognition	★★★	★★★	★☆☆
Low Light Performance	★★★	★☆☆	★★★
All-Weather Operation/Recognition	★★☆	★☆☆	★★★

(Source: Guidehouse Insights)

Cameras

Cameras are passive sensors that can detect either visible or infrared light, generating an image that can be processed with machine vision systems to classify objects. Conventional cameras sense visible RGB light to create clear color images in good lighting conditions. Mono cameras are simple systems that have a single camera lens and sensor to generate 2D imagery suitable for image recognition processing. Stereo camera configurations use twin lenses and sensors to provide a 3D image by merging the two images from these sensors. A stereo camera enables distance perception but has the disadvantages of greater cost, size, and complexity.

Infrared cameras have the advantage of being able to detect objects in the absence of visible light; however, they cannot perceive color and typically produce lower resolution imaging. Shortwave infrared (SWIR) cameras detect non-visible light with wavelengths in the range of 1.0 μm-2.5 μm and enable perception in poor visibility conditions such as in smoke, sandstorms, rain, and fog. Longwave infrared (LWIR) cameras also do not require visible light and operate in the range of 8.0 μm-14.0 μm. LWIR cameras detect thermal energy from the environment to identify objects in low light conditions.

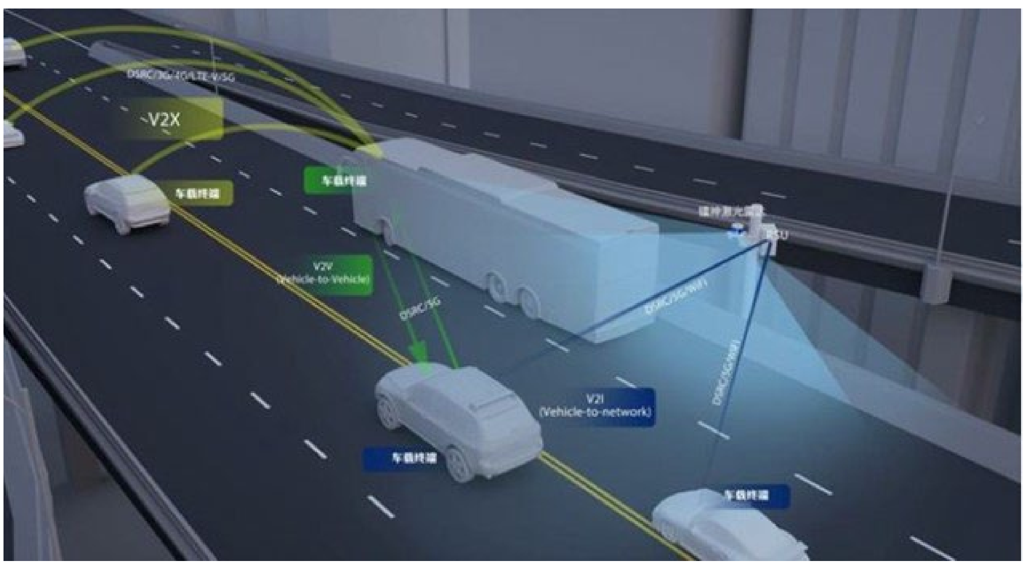
Radar

Radar systems are active sensors that transmit radio wave pulses in the microwave frequency range. These systems measure either the time for an echo or phase shift to calculate an object's speed and distance. Modern automotive radars are typically either short-range radar (SRR) with a range of up to 30 m or long-range radar (LRR) with a detection range of up to 250 m. SRR sensors typically operate in the 24 GHz band while LRR sensors operate in the 77 GHz band. One of the key advantages of radar is the ability to measure distance and speed of an object in poor weather or no light. Automotive radar sensors are relatively inexpensive and provide accurate range and speed measurements. However, they have relatively low resolution and are not useful for object classification. Radar sensors can supplement camera vision in times of low visibility, such as night driving, and improve detection for self-driving cars.

Lidar

Lidar provides a highly detailed and accurate 3D view of the scanned environment, generating point clouds that define detected objects including vehicles, the road, street furniture, and pedestrians. These are active sensor systems functioning in low light conditions, available in a variety of configurations but all sharing common traits. Near or SWIR lasers provide the radiation source and reflected photons are captured by a photosensor to measure the distance and velocity of targets. The first automotive lidar and many of the current units operate in the 905 nm band, while several of the newer designs use the 1550 nm band while a few others fall at wavelengths in between. 1500 nm lidar systems have the advantage of superior performance in high moisture environments such as in rain, fog, and snow.

Figure 1 Lidar-Based RSU Vehicle Identification



(Source: Leishen)

Vehicle to Infrastructure Communications

V2I technologies provide the bidirectional communication link between road vehicles and smart city infrastructure. In addition to traffic information, vehicles can receive safety and efficiency benefits from information including speed limits, parking availability, traffic light timings, roadworks, accidents, and other hazards. Municipalities benefit from live data on congestion levels, safety, and traffic incidents and are provided with the ability to use smart traffic lights to manage city traffic and prioritize emergency vehicles, public transportation, or municipal fleets. Furthermore, municipalities can benefit from the ability to assist with automatic transactions for tolling, congestion zone charges, and parking charges.

AVs are aided by V2I systems because information on potential hazards that are out of the line of sight can be provided well in advance, and information on imminent traffic light timings can help with efficient driving and optimizing traffic flow. Information received from V2I connections provides added input to an AV's ADS as part of the path planning process.

V2I connectivity is wireless and typically involves dedicated short-range communications (DSRC), cellular vehicle to everything (C-V2X), or cellular networks. Therefore, cybersecurity is an essential consideration, as attacks on a V2X system could prevent the transmission of data and potentially result in system failure, compromising vehicle and pedestrian safety. Both DSRC and C-V2X systems are designed to maximize resistance to cyberattacks and information that is transmitted in the network is encrypted and authenticated. Digital signatures are required to validate received messages to protect the overall system and individual vehicles.

Although offboard sensors can provide superior perception in some instances, they can never fully replace on-vehicle perception and control. Connectivity cannot be guaranteed in all circumstances, and minimization of system latency is critical for safety. However, they are valuable when augmenting on-vehicle sensors and can enable a variety of smart city applications. In addition to enhancing the perception of AVs, offboard sensors can facilitate automated valet parking (AVP) by providing a detailed view of a parking facility and information on available parking bays. Also, they can help cities with traffic and parking enforcement and focused monitoring for accident hotspots. Information gathered by offboard sensors is transmitted to vehicles via wireless communication technologies.

Wireless Vehicle Communication Technologies

DSRC

DSRC is the most established option for the real-time connectivity of V2I and V2V systems. The development of DSRC was initially based on Wi-Fi and the technology has seen deployments since 2017. For vehicle connectivity applications, DSRC adheres to the Institute of Electrical and Electronics Engineers (IEEE) 802.11p wireless access in vehicular environment (WAVE) standard, using the 5.9 GHz intelligent transportation system (ITS) frequency band to provide a communication range for distances of under 1 km and typically around 300 m. DSRC has been deployed for automotive applications mainly in Europe, Japan, and North America.

C-V2X

C-V2X is a more recent vehicle connectivity development, based on LTE with significant deployments only commencing as recently as 2021. Like DSRC, the technology uses the 5.9 GHz ITS frequency band to enable local V2I and V2V communications but can achieve a direct transmission range exceeding 1 km. Also, C-V2X can connect with 4G LTE and increasingly 5G cellular networks for a wider transmission range to facilitate vehicle to network and V2P applications that include communicating with cyclists and pedestrians via their smartphones.

Despite the similarities between DSRC and C-V2X, the systems are not interoperable. To date, China has been the main market for C-V2X, and the technology has been included in the government's plans to extend the rollout of ITS within the country. However, an increasing number of automakers in Japan, Europe, and the US have recently announced plans to deploy C-V2X, including Ford, Audi, and Toyota.

4G LTE and 5G Connectivity

The majority of C-V2X implementations have used 4G LTE connectivity, a wireless broadband standard first launched in 2008. Although 4G LTE is adequate for current V2X applications, 5G, the next generation of network technology, has started to emerge globally, featuring several advantages over 4G LTE. 5G provides a robust connection with latency as low as 1 ms, which is important for safety-critical applications such as for AVs that require highly reliable connections and fast response times. Moreover, 5G is capable of theoretical data transfer rates of 10 Gbps, which is up to 100 times faster than 4G LTE. High data bandwidths are valuable for other automotive applications such as for infotainment, high detail navigation maps, and audiovisual streaming services for passengers.

As well as the performance benefits of C-V2X over DSRC, the further network-assisted capabilities of C-V2X and 5G compatibility is increasingly attracting the attention of automakers looking for a futureproof V2X connectivity solution. 5G-compatible C-V2X systems have been launched by Audi for the A6 and A7 models for the Chinese market and are expected to be available in other regions from 2023.

V2X Technologies for Automated Driving Projects

A number of projects have demonstrated the benefits of V2X for a variety of applications. In addition to proving the technical merits of these systems, these projects have assessed the commercial readiness of these technologies.

Autonomous a2z: Smart City Solutions – Lidar Infra System

Autonomous a2z is a South Korea-based startup founded in 2018. The company develops autonomous driving technologies with a number of ongoing pilots on public roads in its home country. To date, a2z has accumulated more than 180,000 km of AV driving, greater than any other ADS developer in South Korea. Furthermore, a2z has pioneered the commercialization of paid robotaxi and automated shuttle services in the country.

Figure 2 Autonomous a2z and Kakao Mobility Robotaxi

(Source: Autonomous a2z)

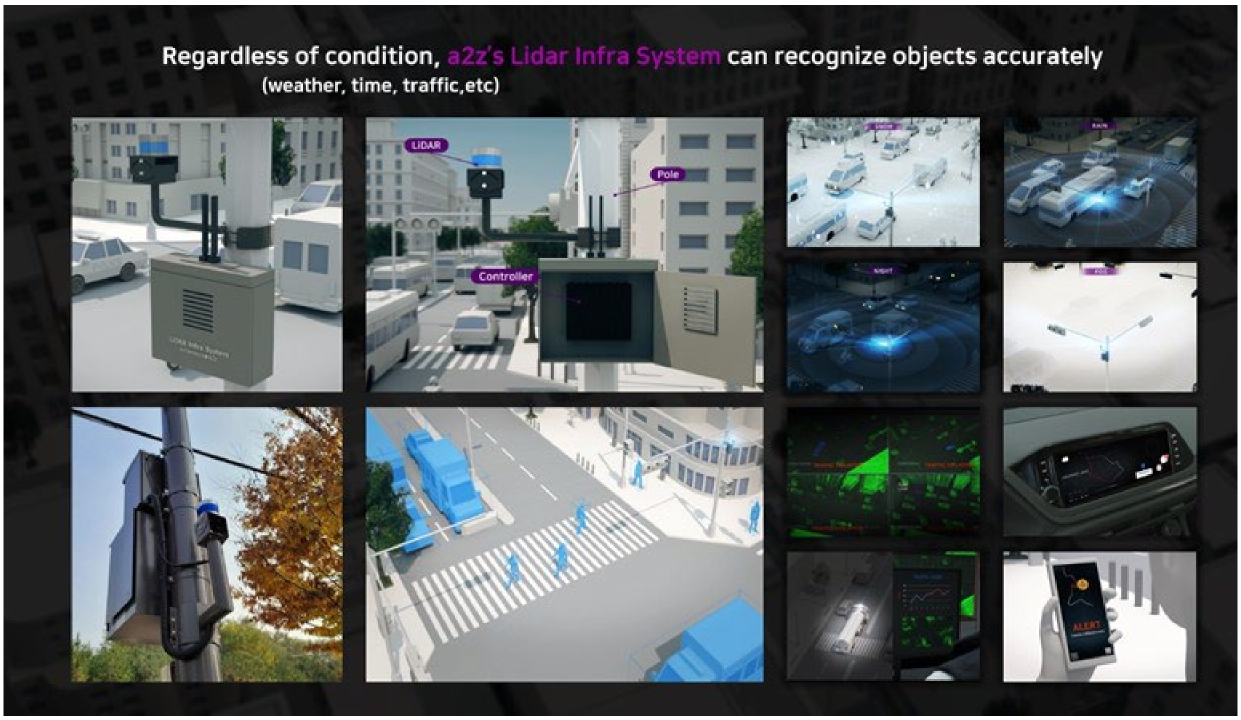
Table 2 Autonomous Driving Mileages as of December 2021

Competitor	Country	Number of AVs	Autonomous miles completed
Waymo	USA	693	2,325,843
GM Cruise	USA	138	876,105
Pony.AI	USA/China	38	305,617
Zoox	USA	85	155,125
Autonomous a2z	South Korea	21	116,639
Nuro	USA	15	59,100

(Source: California Department of Motor Vehicles)

a2z has been developing its Smart City Solutions suite to enable autonomous mobility for both fixed route and on-demand mobility services. One of a2z's Smart City Solutions is their Lidar Infra System, which is based around a single lidar sensor and a control unit, which are mounted on existing roadside traffic infrastructure such as on traffic lights. The system is capable of real-time object recognition and can identify the different classifications of road users such as cars, pedestrians, and cyclists with their precise location (within 10 cm), speed, and direction. Traffic infrastructure, such as traffic lights and lane markings, is also accurately recognized. A proprietary HD mapping system using an efficient vector map and localization algorithm is key to the rapid processing resulting in overall system latency of less than 500 ms. Information on traffic and weather conditions is gathered and the system can identify traffic offences and the functioning of traffic lights. Information collected by the system can be shared in a number of ways, for example sending appropriate data to a traffic control center or to AVs. Additionally, the information can be sent to drivers of non-AVs and pedestrians.

Figure 3 a2z's Lidar Infra System

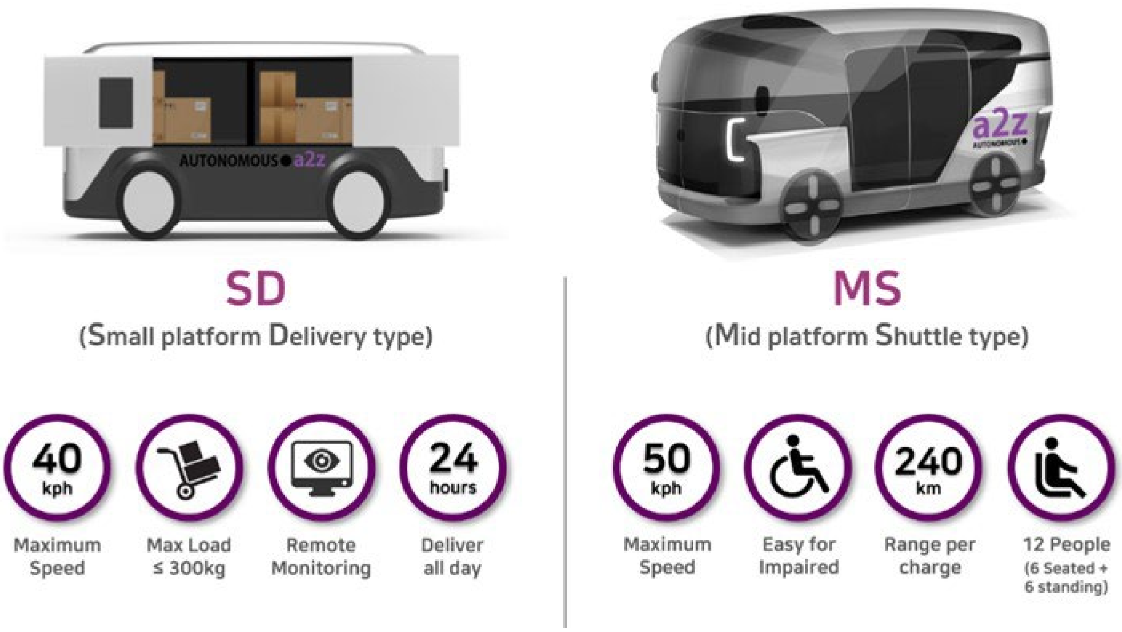


(Source: Autonomous a2z)

The objectives of developing a2z's system are to improve traffic and pedestrian safety and to support traffic management as part of a city's ITS. The benefits of a2z's system include its relatively low hardware and installation costs as a result of its simple architecture, real-time object recognition with minimal latency, accurate and reliable operation in all weather and lighting conditions, and the ability to share information with third parties.

The Lidar Infra System has been deployed in the municipalities of Pangyo, Sejong, Daegu, and Seosan in South Korea. In Pangyo, the objective has been to demonstrate the guidance of AVs at junctions. Vehicles entering the monitored junction box are identified and a signal is sent to the onboard unit on AVs to provide guidance to enable them to perform right hand turns at the junction. In Sejong, the purpose of the pilot is to ensure the safety at a school intersection by gathering real-time data on pedestrians and traffic at the intersection and sharing this information with approaching AVs. Traffic violations and jaywalking pedestrians are also identified to inform AVs and potentially city traffic enforcement. a2z's V2X system is being demonstrated in certain districts of Daegu, utilizing 5G connectivity. The Seosan demonstration is primarily focused on providing notifications on the status of a junction, with information on current vehicle activity within the junction.

Figure 4 a2z's Small Platform Delivery Vehicle and Mid Platform Shuttle



(Source: Autonomous a2z)

a2z is expanding its technology offering to develop AVs that are fully compatible with the Lidar Infra System to complete its integrated Smart City Solution. The company is developing an EV platform named Smart City Platform, which includes a midsize variant for up to 12 passengers to be used for passenger transportation as well as delivery, patrol, and street cleaning applications. A midsize platform is also being developed to cater for logistics use cases. a2z has completed AV projects with the Korean IT company Kakao to demonstrate the integration of the company's technology with traffic control and mobility service platforms for robotaxi and bus rapid transit shuttle applications. To aid the transition from being primarily a software company to an automaker, a2z has forged partnerships with leading Korean Tier 1 automotive suppliers including SL Corporation, Sambo Motors, and PHC Valeo.

Furthermore, a2z is in collaboration with KT, a major Korean telecommunications company on AV projects to develop a 5G-based communication system for the Smart City Platform. The key objective of this partnership is to develop a dedicated 5G module to be embedded into the Smart City Platform. These projects include local government pilots to address the Korean government's V2X standardization for this 5G module. Technologies, including real-time kinematic (RTK) and local dynamic map (LDM), have been applied during these projects with the aim of enhancing the safety and efficiency of autonomous cooperative driving. RTK and LDM enable the transmission of data and precise routing information to AVs. Additionally, a similar project was completed for the Republic of Korean Air Force based on the application of mobile edge computing for 5G convergence. This project resulted in the deployment of an autonomous shuttle bus for the Air Force in December 2021.

Bosch and Ford: AVP

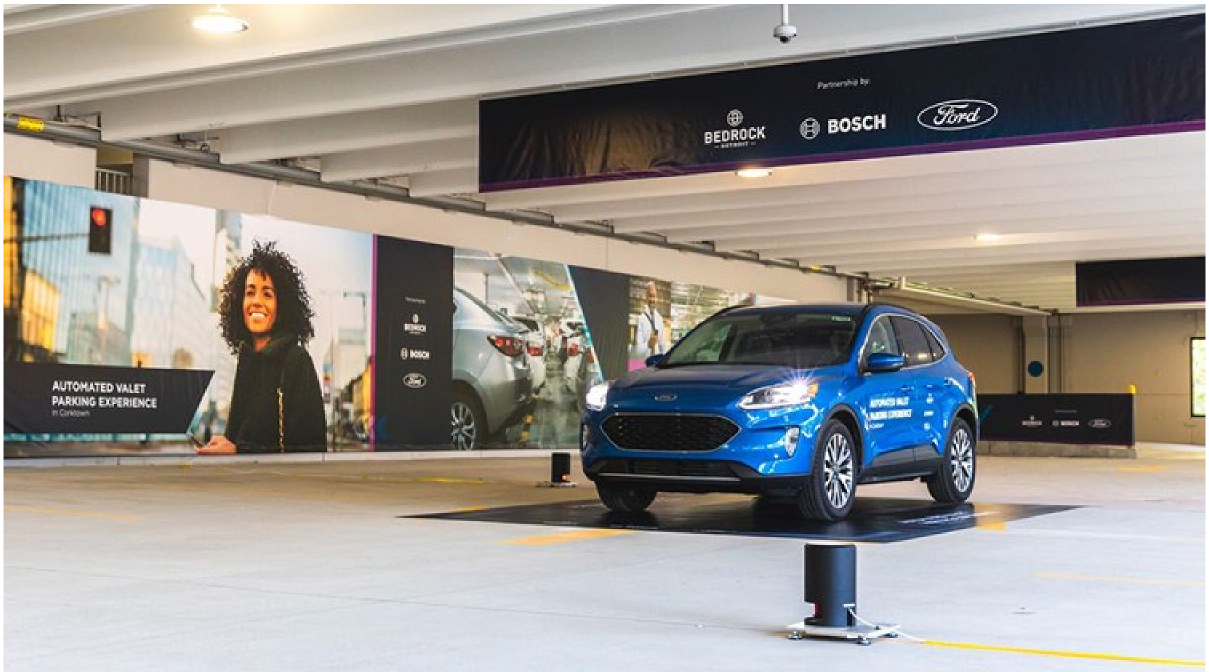
Bosch and Ford have collaborated to develop and trial an AVP solution that does not require highly automated vehicles. Compatibility with the AVP system requires connected vehicles with remote starting, automatic transmission, and electronic steering and parking brake. Bosch and Ford recognize three categories of AVP solution: Type 1 systems are based solely on onboard sensors, Type 2 systems are infrastructure-based, and Type 3 systems combine the other two systems and require sensors on the vehicle and in the parking infrastructure.

The AVP system that has been demonstrated in Ford's Smart Parking Lab in Detroit is a Type 2 system, relying on the parking facility's infrastructure to park the vehicle, which maximizes its immediate applicability to currently available vehicles. Detroit-based real estate firm Bedrock and Michigan's Office of Future Mobility also partnered with Ford and Bosch. The system is based on an array of stereoscopic cameras that are mounted above parking bays. Each parking bay requires two sets of cameras that monitor the occupancy of the bay and the positioning of self-parking vehicles. Cameras are also sited at challenging locations such as ramps and corners. The array of cameras is connected with Ethernet cables to a control unit in the server room, normally within the parking structure.

AVP is triggered by the driver using an OEM smartphone app then leaving the vehicle in a drop-off area. During testing, the Ford Pass app was used to initiate the parking process. Once AVP has been requested, the commands are sent from a cloud server and processing is done locally at the AVP server where the system identifies the optimum parking space and communicates with the vehicle using a Wi-Fi connection from the local server. The system sends signals to guide the vehicle to the parking space. Overall system latency is below 500 ms and the system safely stops the vehicle if the cameras detect any obstacles such as passing pedestrians. At the parking location, the system precisely maneuvers the vehicle into the bay. When the driver returns, the car is summoned through the app and the system guides the car to a pick-up area. Payment for parking is also automated based on the drop-off and pick-up times for the vehicle.

Benefits of this AVP system include a 20% increase in parking efficiency as a result of the system enabling cars to park closer together because a driver does not need to exit the vehicle. This benefits parking operators that can improve their parking revenue from increased capacity. Customers benefit from the convenience and saved time looking for parking spaces. Safety is another important benefit; the wide arrays of cameras deployed can identify potential obstacles early plus parking maneuvers are more precise, reducing the risk of accidental damage. AVP can also enable other services such as EV charging and vehicle cleaning before the customer returns to the vehicle.

Figure 5 Bosch and Ford's AVP



(Source: Bosch and Ford)

This AVP system is close to commercial readiness. Bosch has also partnered with Daimler and parking operator APCOA in a separate AVP demonstration in Stuttgart airport. This particular project is ready to be scaled to full commercial operation pending approval from the city authorities. Another result of this partnership is the piloting of AVP in 2019 at the Mercedes-Benz Museum in Stuttgart. The technology developed is implemented in both the current Mercedes S Class and EQS EV.

Ford and Quantum AI: Smart Infrastructure Nodes

In collaboration with autonomous driving technology subsidiary Quantum AI, Ford has developed a Smart Node system that is equipped with lidar, radar, and cameras as found onboard AVs. This system has been designed to be installed above complex traffic intersections to provide SAE Level 4 AVs with a bird's eye view of the road ahead and information on road users, pedestrians, and road infrastructure. The sensor stack identifies potential hazards from analyzing the real-time precise location and movement of vehicles, bicycles, and pedestrians. This data is sent via a cellular connection (C-V2X) and complements the onboard sensors of AVs, quickly providing valuable information on the road environment before the vehicle reaches the intersection and providing extra information when the immediate surroundings are obscured by obstacles such as buildings or other vehicles. Data collected by the system is not personally identifiable and is anonymized to protect data privacy.

Ford and Quantum AI are piloting their Smart Node system in Detroit as part of a project to deliver senior residents with groceries on a fixed route between Ford's Resource and Engagement Center in central Detroit to a nearby senior community. The project plans to make deliveries with a low-speed automated shuttle to the senior community over 6 months, totaling more than 10,000 pounds of fresh groceries over this period, while learning about supporting communities that are poorly served by mobility services. Another key objective is learning about commercializing AV and how future automated ride-hailing and food delivery services could best serve customers.

Figure 6 Ford and Quantum AI Smart Infrastructure Node

(Source: Ford)

The automated shuttle has a safety driver onboard and is supported by remote operators to take control of the vehicle in unexpected situations. Smart nodes are installed at major intersections on this fixed route, providing the automated shuttle with information on what is happening at the complex intersections before the vehicle arrives. Information from the smart nodes is fused with data from the onboard sensors at street level to provide enhanced perception of the road ahead to improve safety and vehicle efficiency.

Ford and Quantum AI started testing their Smart Nodes on public roads first in 2020 in Saline, Michigan, and then in 2021 in Miami, Florida, at busy intersections with significant pedestrian and road traffic. The testing was conducted with non-automated Ford vehicles, where the drivers were notified of potential hazards at the intersection, for example pedestrians about to cross the road or vehicles travelling at high speed that would otherwise be undetected.

Conclusions and Recommendations

Smart city infrastructure can offer vital benefits to AVs, primarily improving the safety of the vehicles, their occupants, and other road users including cyclists and pedestrians. Offboard sensors overcome line-of sight limitations to extend the perception of on-vehicle sensor systems, providing increased reaction time for AVs in the event of a potential hazard. Moreover, V2X systems can deliver valuable benefits to cities, including traffic management and monitoring of incidents and accident hotspots, to improve traffic flow and reduce urban vehicle emissions.

Cameras, lidar, and radar are the key offboard sensors to provide useful information to vehicles, and each has their advantages in various applications. The most sophisticated V2X sensor is lidar, which provides high resolution and accurate 3D perception in all weather and lighting conditions. Lidar typically comes at a higher cost, though, for RSU applications, only a single sensor is required. Radar can offer perception in difficult conditions at lower cost, though multiple units are required that have low resolution and weak object recognition capability. Therefore, ideal applications are where radar supports other sensor types. Cameras are another low cost sensor option, capable of color imagery and depth perception in stereo configurations. However, multiple units are required in V2X installations and perception is weak in poor lighting conditions. Cameras are an optimal solution for AVP applications inside parking structures where an array of cameras can surveil a wide area.

Cities

The safety benefits of V2X infrastructure for cities should be explored to prepare for the future wider deployment of AVs on their streets. Cities should collaborate with V2X technology suppliers and auto OEMs to pilot these technologies to monitor complex intersections and assess the potential effect on reducing accidents and protecting vulnerable road users. Traffic management is another benefit that should be assessed for its impact on traffic planning and reducing congestion. Furthermore, cities should evaluate the revenue potential of V2X from enabling charging for tolling, congestion charging, parking, and providing information for mobility services such as ride-hailing.

Automakers

Automakers should increase their development of V2X compatibility with further collaborations with technology suppliers. As a result, they can substantially improve the perception, path planning, and hence safety of their forthcoming AVs. They should assess the future potential of 5G connectivity with C-V2X in not only improving V2X performance but also enabling faster data connections for streaming services.

Parking Operators

Parking operators should model the potential increased parking revenue of AVP arising from optimizing parking facility utilization and providing additional value to customers. Moreover, they should work with technology suppliers to provide solutions that can enable non-automated connected vehicles to benefit from AVP.

Acronym and Abbreviation List

ADS .... Automated Driving System

ADAS .... Advanced Driver Assist System

AI .... Artificial Intelligence

AV .... Automated Vehicle

AVP .... Automated Valet Parking

C-V2X .... Cellular Vehicle to Everything

DSRC .... Dedicated Short-Range Communications

EV .... Electric Vehicle

Gbps .... Gigabit per Second

GHz .... Gigahertz

GPS .... Global Positioning System

HD .... High Definition

IEEE .... Institute of Electrical and Electronics Engineers

ITS .... Intelligent Transportation System

LTE .... Long-Term Evolution

LRR .... Long-Range Radar

LWIR .... Longwave Infrared

ms .... Millisecond

OEM .... Original Equipment Manufacturer

RGB .... Red Green Blue (Light)

RSU .... Roadside Unit

SAE .... Society of Automotive Engineers

SRR .... Short-Range Radar

SWIR .... Shortwave Infrared

V2I .... Vehicle to Infrastructure

V2P .... Vehicle to Pedestrian

V2X .... Vehicle to Everything

WAVE .... Wireless Access in Vehicular Environment

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Scope of Study

Guidehouse Insights has prepared this white paper, commissioned by Autonomous a2z, that details how smart city infrastructure can be used to expand the situational awareness of AVs. The paper provides an overview and comparison of the key sensor technologies that enable vehicle to everything (V2X) systems. Examples of leading projects in North America and South Korea are provided for applications that include enhancing the perception of AVs in complex traffic scenarios on public roads and for enabling AVP within parking structures. Recommendations are provided for cities, automakers, and parking operators to take advantage of the safety, economic, and traffic optimization benefits offered by V2X systems.

Sources and Methodology

Guidehouse Insights' industry analysts use a variety of research sources in preparing research reports and white papers. The key component of Guidehouse Insights' analysis is primary research gained from phone and in-person interviews with industry leaders including executives, engineers, and marketing professionals. Analysts are diligent in ensuring that they speak with representatives from every part of the value chain, including but not limited to technology companies, utilities and other service providers, industry associations, government agencies, and the investment community.

Additional analysis includes secondary research conducted by Guidehouse Insights' analysts and its staff of research assistants. Where applicable, all secondary research sources are appropriately cited within this report.

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