WHITE PAPER
IMAGING RADAR

4D IMAGING RADAR: SENSOR SUPREMACY FOR SUSTAINED L2+ VEHICLE ENABLEMENT

Super-fine resolution radar mapping proves a compelling, cost-effective alternative to Lidar

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The advent of 4D imaging radar technology for automotive sensing and autonomous driving applications has reshaped the timetables and economics of our evolution from L0 to fully autonomous L5 vehicles. Radar's newly tapped ability to enable precise environmental mapping dramatically enhances vehicles' overall sensing and awareness capabilities, and in so doing, redefines industry expectations for radar's role going forward relative to camera sensors and particularly lidar sensors.

On a broad range of performance and reliability metrics, imaging radar closes the gap with lidar and even outperforms it in some dimensions, at commercial cost structures that lidar does not yet approximate — and may never. As these sensor technologies begin to overlap in functionality, their respective roles and costs must be closely assessed.

In parallel, key questions have emerged around timing and duration of the automotive industry's critical pivot from L2 to L3 safety and automation enablement. L2+ has become the hot new battleground while OEMs navigate the many design complexities required to achieve L3 conformance.

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As the overhead associated with full L3 remains substantial, primarily due to redundancy necessary to account for not having the driver present as a backup, the attention has turned to and is driving strong growth at L2+, where L3 capabilities are provided, yet with the driver available as a backup, reducing the additional need for redundancy.

LEVELS OF COMPLEXITY

With that, it's helpful to assess 4D imaging radar's potential impact on ADAS and AD applications in the context of SAE's five levels of driving automation, and in particular the hugely consequential difference between L2 and L3. At L2, the driver's attention is always required; the driver is ultimately responsible for vehicle safety and can be held liable in the event of an accident. Beginning with L3, however, the onboard safety automation is expected to be sufficiently robust such that the vehicle OEM assumes the accident liability.

There's also a key distinction from L3 to L4/L5. Whereas the intervention of the driver is required in some circumstances at L3, at L4 and L5 driver intervention might be available if requested but must not be assumed — and in some L5 use cases, not possible. At a minimum, L4 and L5 vehicles are expected to be able to safely bring themselves to a stop under any circumstances, with no human intervention.

These AD levels also introduce new system redundancy requirements as driving responsibility is increasingly assumed by the vehicle. At L3, the driver needs to be able to take control of the vehicle in challenging conditions, but will otherwise be "eyes off, hands off." It could take up to one minute for the driver to gradually assume full control in these scenarios, and the levels of redundancy required for this single function — safely transferring control from vehicle to driver — will impose significant system complexities and costs. As a consequence, the yet-to-be determined number and configuration of camera, radar and lidar sensors per vehicle needed to achieve L3 conformance, and the delta to the typical L2 sensor configuration, will hold huge implications for OEM manufacturing costs.

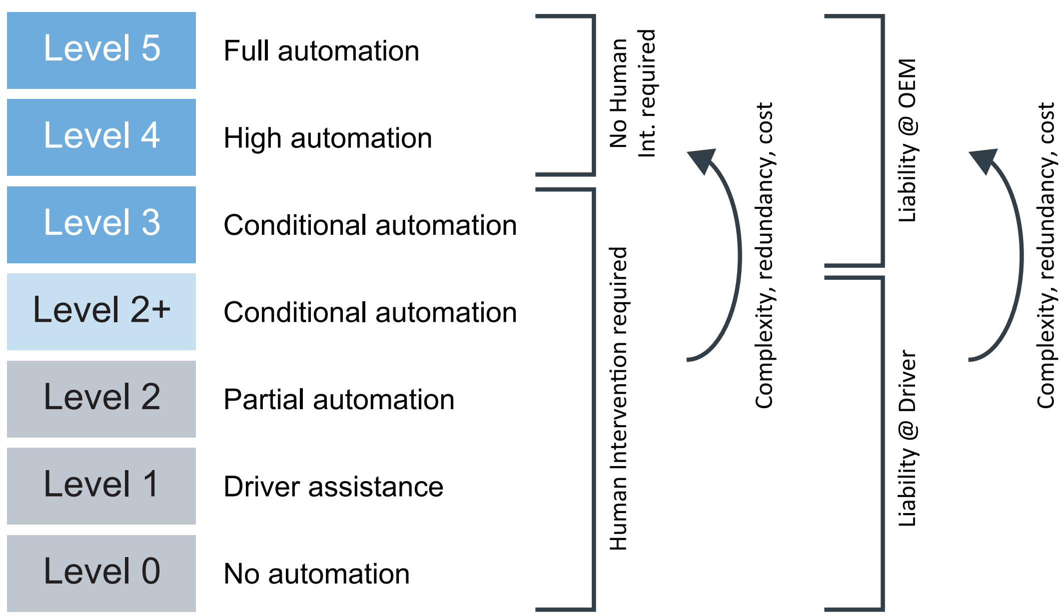


Figure 1: Levels of Advanced Driving Assistance Systems and Autonomous Driving

This helps to explain the emergence of L2+ as a means for OEMs to minimize the cost increase from L2 while beginning to offer customers advanced ADAS features that approach L3 automation without fully crossing the L3 threshold that transfers liability from driver to OEM. L2+ leverages similar sensor and semiconductor content relative to L3, so manufacturing costs can be readily contained at L2+ when factoring out the added cost of implementing system redundancies needed for vehicle-to-driver control transfers at L3. Meanwhile, consumers will notice and appreciate the new safety and comfort features rolled out to them in the coming years from the many OEMs competing for market differentiation on the road to L3, L4 and L5.

L2+ — THE NEXT KEY BATTLEGROUND

As these new safety and comfort features accumulate at L2+ at a price point consumers find palatable, questions arise around their willingness to pay considerably more for the additional system redundancy required for L3 conformance.

For OEMs, L2+ allows them to sidestep the significant costs needed to address redundancies and corner cases at L3 — costs that could render these vehicles commercially less attractive. L2+ also allows OEMs to roll out advanced safety and comfort features step-by-step, allowing more time for sensor technologies to mature for commercial-scale adoption at higher levels of autonomous driving. The driver can continue to provide the necessary redundancy in the interim, and the OEMs could achieve a more optimized balance between features and costs.

OEMs are ultimately left to ponder these important questions as they approach L3: If the cost burden for achieving L3 system redundancy is similar to the cost burden anticipated at L4, why linger at L3 at all? Will customers be willing to pay considerably more for L3 safety system redundancy if ultimately their driving attention will still be required anyway? While there may be no OEM consensus on these questions, it is reasonable to believe that the volume of L2+ vehicles will significantly exceed that of L3 in the years to come.

A recent Yole Development report indicates that L4/L5 market penetration will remain in the low single digits until at least 2030 , and a portion of it will be consumed as robotic cars. Meanwhile the uptake for L2+ vehicles should continue to grow steadily as L0–L2 penetration begins to subside, with L2+ likely achieving almost 50% market share by 2030. As such, it is expected that L2+ will be in the focus of attention for automotive OEMs in the coming decade.

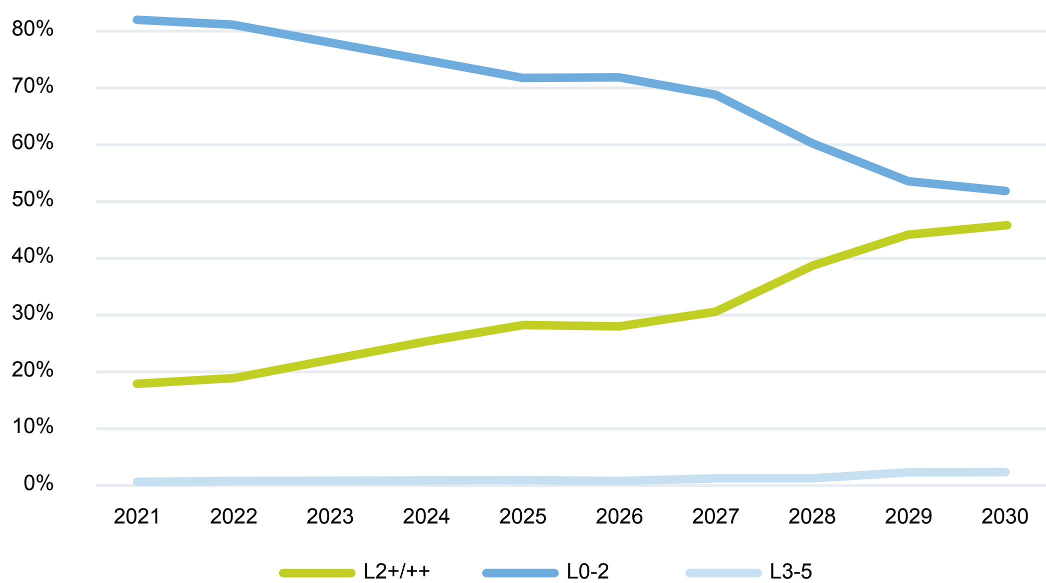


Figure 2: Market Penetration Forecast of Autonomous Driving (2021–2030)

THREE SENSORS, NO SINGLE SOLUTION

The merits of 4D imaging radar for L2+ vehicles can be fully understood within a higher-level analysis of the three primary sensing technologies enabling ADAS and AD: camera, radar and lidar. Ultimately there is no one-size-fits-all sensor solution — each comes with unique strengths and weaknesses and can complement and/or provide redundancy to the other sensor types.

Camera and radar sensors are of course already widely deployed today, owing to the maturity and affordability of the two largely complementary technologies. Lidar by its nature isn't functionally complementary to camera or radar and will therefore likely serve as a redundancy layer for both.

Camera sensors' unique ability to detect RGB color information, combined with its megapixel resolution, will continue to make them indispensable for "reading" traffic signs and other applications benefiting from improved accuracy in object recognition and classification.

But camera technologies' effectiveness and reliability become compromised in widely varying lighting conditions, as well as harsh weather and road conditions. Paradoxically, there are technologies coming to market that will automatically remove moisture and debris from vehicle camera lenses, but these mechanisms will raise BOM costs and, ironically, introduce additional mechanical vulnerabilities affecting system robustness.

Cameras' ability for distance and speed measurement will also remain extremely limited. Certainly speed and depth estimation can be obtained from a stereo camera configuration; nevertheless, the accuracy is limited — a shortcoming that's compensated for at the radar layer.

LIDAR — PROVIDING PERFORMANCE PREMIUM FOR CORNER CASES

Lidar's primary differentiating features are its ultra-precise angular resolution down to sub-degrees both horizontally and vertically, and its fine resolution at range, owing to the extremely short wavelengths and pulses utilized. These strengths make lidar well suited for high-resolution 3D environment mapping, providing the ability to accurately detect free spaces, boundaries and the vehicle's own localization.

Lidar shares some common drawbacks with camera sensors, however. Lidar's abilities to estimate velocity and detect objects far ahead are quite limited compared to radar sensors. What's more, lidar's susceptibility to harsh weather and road conditions introduces higher costs to address robustness and maintenance challenges.

New lidar technologies have been emerging in the past years, such as solid state lidar, MEMS lidar or electronically scanning lidar. The new technologies are aiming at making lidar overall more "friendly" to automotive applications in terms of size, cost and robustness. While they demonstrate improvements over mechanical rotating lidars, in general, these technologies still need time to further mature and catch up with the maturity level of other ADAS sensor counterparts. Yet the biggest hurdle for wide adoption of lidar into mainstream passenger vehicles remains the cost. According to a recent OEM assessment, the cost of a lidar in 2021 at low volume is about ten times that of a 12-TX and 16-RX imaging radar with four cascaded radar transceivers. While the cost of both lidar and radar is expected to drop over time, it is expected that even by 2030, when lidar will be seeing some volume in higher-level autonomy use cases, the cost of lidar will remain twice the cost of radar.

Looking to the foreseeable future, lidar will continue to provide an extra performance premium to handle corner cases arising in complex driving scenarios. As such, it will remain an important part of redundancies required for L4 and L5 autonomous driving, where its price premium will be tolerable.

4D IMAGING — RADAR'S BIG LEAP AHEAD

Radar remains distinguished among the sensor modalities for its highly accurate speed and distance measurement capabilities. While lidar illuminates the target scene with sparsely placed laser beams, radar illuminates the scene seamlessly. At greater distances, lidar may miss smaller targets altogether if the targets are situated between the sharply defined laser beams. This makes radar a much more reliable sensor for longer-range operation. Radar's detection range has extended up to and in the future may reach beyond 300 meters — far beyond what camera and most lidar sensors can provide. What's more, radar works reliably in all weather and light conditions unlike its camera and lidar counterparts. Environmental debris and/or water drop refraction introduced by adverse weather conditions will not impair radar operations. Operating in mmWave frequencies, radar can also transmit through dielectric materials, such as the vehicle bumper, and requires no physical opening for its aperture to illuminate — a better choice for both robustness and aesthetics.

Radar's primary weaknesses are its inability to capture color information and its limited angular resolution compared to camera and lidar sensors. But recent advancements in 4D imaging radar have enabled significantly enhanced angular resolution capabilities, and in doing so, has helped to close the performance gap with lidar. Opening up new possibilities for radar innovation on the path to L5 vehicle automation, 4D imaging radar could assume the majority of the workload for future sensor suites targeting L2+ all the way up to fully autonomous vehicles.

Compared to conventional radar sensors, 4D imaging radar is capable of calculating the space distance as well as the angle of arrival for both azimuth and elevation direction. In addition, it provides angular resolution down to sub-1 degree compared to the 5 to 8 degrees of resolution enabled with conventional automotive radar.

This is made possible with MIMO (Multiple Input Multiple Output) antenna arrays that generate large numbers of virtual channels, which are proportional to the radar aperture and inversely proportional to the angular resolution. The more virtual channels, the finer the angular resolution. MIMO certainly doesn't come without challenges, as it introduces artifacts and ambiguities to the received radar signals. Such artifacts and ambiguities, however, can be mitigated with advanced MIMO waveforms.

MIMO waveform construction and artifacts mitigation are by themselves dedicated areas for innovation. NXP can provide its customers with state-of-the-art solutions for mitigating challenging MIMO artifacts of commonly used MIMO waveforms. The design and implementation of these advanced techniques are closely coupled to the underlying NXP radar processors, allowing customers to extract most performance out of synergy from the aligned software and hardware development.

With these improved capabilities, radar sensors are for the first time able to deliver high resolution point cloud outputs, enabling a higher resolution mapping of the environment and scene awareness that's on par with lidar today. Yet they come at a much lower cost, making them suitable for widespread volume adoption. On top of that, 4D imaging radar opens up a unique capability of multi-mode operating — detecting objects simultaneously in all ranges, from near to the farther end of up to 300 meters.

4D imaging radar equips vehicles to make decisions that can't be addressed with conventional radars — determining if a tunnel is safe to drive through, or if an obstacle in the driving lane is safe to drive over, for example. These advanced capabilities qualify 4D imaging radar to provide redundancy or backup to camera and lidar sensors in adverse weather and road conditions.

With 4D imaging radar, it becomes possible to detect, separate and track multiple stationary and/or moving objects up to 300 meters ahead, even when objects are in close vicinity of each other. This is well beyond the detection range of both cameras and lidars.

Given its sub-degree resolution, accurate distance and speed measurement, the simultaneous multi-mode detection up to 300 meters — radar sensors provide the longest range among all sensor types. Added to the ability to operate independent of environmental conditions, radar sensors are anticipated to become the most fundamental, versatile and robust sensing modality for the sensor suites of vehicles of any AD level.

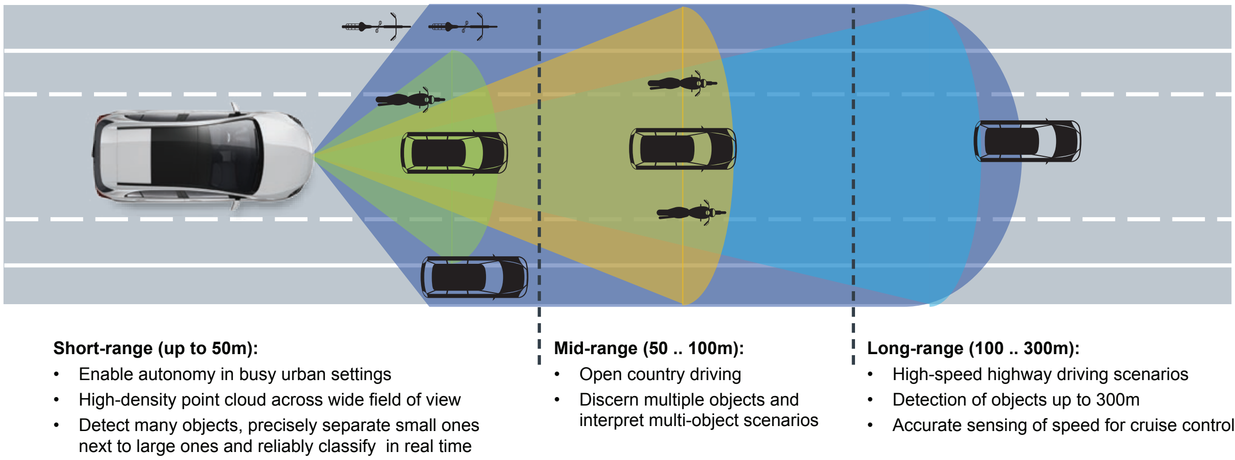


Figure 3: Simultaneous triple beam multi-mode for short-, mid- and long-range capability

CHALLENGING USE CASES

Camera and radar sensors complement each other well and are destined to be widely deployed from L1 to L5. At L2, sensor fusion is required for the vehicle to exert lateral and longitudinal control simultaneously. At L2+ and L3, the vehicle is expected to combine multiple lateral and longitudinal controls in order to handle significantly more complex, task-oriented use cases executed by the vehicle itself under predefined, limited conditions.

Highway pilot provides a good illustration. When the ODD (operation design domain) is sufficiently met, the vehicle is expected to drive at speeds up to 130km/h, initiate lane change and completely overtake the slow-driving car ahead. This advanced capability requires the ability to look far ahead to identify danger as early as possible and reliably secure free space and safe distance from cars and motorbikes in neighboring lanes to ensure a safe overtake maneuver. Conventional radars can't meet this requirement, because they have limited detection range and lack the angular resolution to identify and secure the free space that's needed.

At L2+, the driver is expected to navigate difficult maneuvers like this when required. Lidar would merely provide an additional layer of redundancy that's already met by the human driver, and therefore could be left out of L2+ designs for cost optimization reasons.

At L3, a vehicle will need to handle more corner cases than an L2+ vehicle; even though the driver is expected to take over the vehicle controls when requested within a time window up to one minute, a lidar might be desired for additional redundancy. However, the perceived value versus the price tag might make this approach less palatable for customers when compared to L2+ vehicles offering similar features. The take rate of L3 vehicles therefore remains a question, before L4 and L5 take hold in the market.

Urban pilot is another good example of a complex, task-oriented use case. In order to safely drive up to 70 km/h in a hazard-rich urban environment that's considerably more complex than highway pilot scenarios, a vehicle should be able to safely reconcile occluded pedestrians and pets crossing unexpectedly into traffic. In some parts of the world, time-bounded urban streets that automatically reconfigure into one or two lanes depending on the time of day must also be accounted for, most likely at L5.

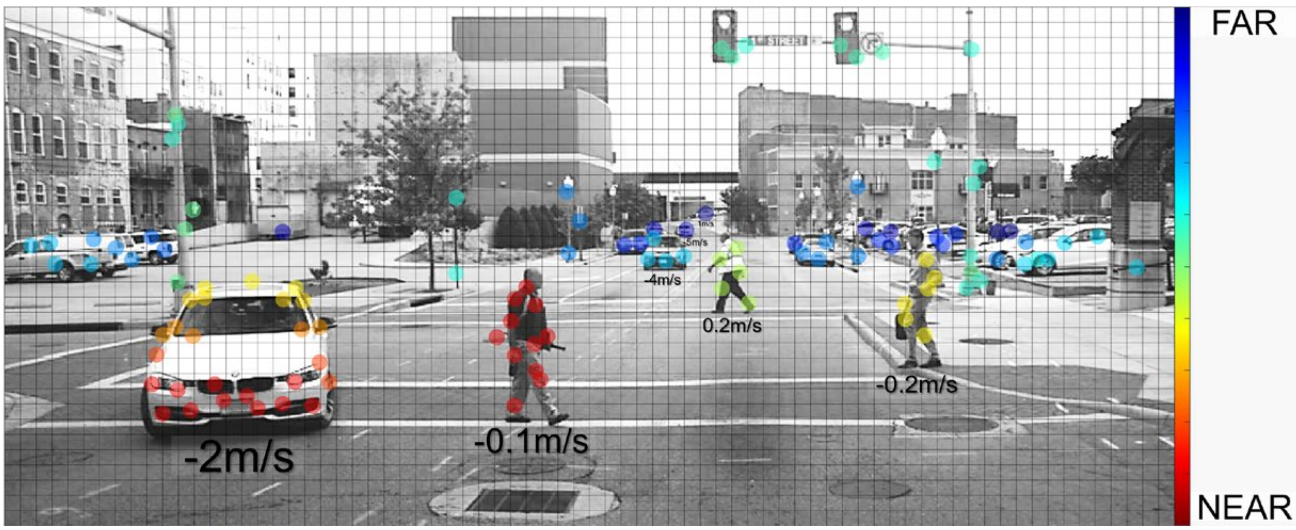
Highly accurate object recognition and classification become essential in this use case, as does a highly detailed environmental mapping capability. At L4 and L5, the driver isn't required to take over the vehicle, so in order to bring the vehicle to a safe stop as the very last resort, full redundancy is no longer an option — it's a must-have.

For this reason, L4 and L5 vehicles are expected to leverage all three primary vehicle sensor modalities — camera, radar and lidar — integrated within the sensor suite. Given that high-performance 4D imaging radar sensors can help achieve L3 and higher safety conformance without the need for more than one lidar per vehicle for redundancy purposes, OEMs are well positioned to achieve aggressive cost targets at the sensing and processing layers.

CONCLUSION

The emergence of commercially viable 4D imaging radar technology holds major implications for ADAS sensor suites targeted for deployment at L2+ and higher, enabling broad proliferation of L2+ safety and comfort features and a path towards full L4/L5 automation. The relative strengths of camera, radar and lidar sensors will determine the role and significance of each sensing technology for each of the AD levels. Radar sensors in particular are poised to become the most fundamental sensor, complemented by camera for L2+ and L3, and by camera and lidar for L4 and L5.

The recent introduction of NXP's high-performance S32R45 radar processor provides a clear, cost-effective pathway for OEMs to enable advanced 4D imaging radar capabilities for L2+ and higher at commercial volumes and cost structures, thanks to its smart approach combining NXP's sophisticated radar signal processing IPs with highly advanced 16nm FinFET CMOS technology. For more information, visit www.nxp.com/S32R45.



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