TRIEYE

WHITEPAPER

NAVIGATING THE CHALLENGES OF LOST CARGO DETECTION

AUTOMOTIVE

TABLE OF CONTENTS

01 **MOTIVATION**

The use case of identifying lost cargo and taking the appropriate driving maneuver is defined in the UN regulation R157 (ALKS - Automated Lane Keeping Systems). The regulation describes the required control of the lateral and longitudinal movement of the vehicle for travelling speed of up to 130 km/h and for extended periods of time without driver intervention (meaning, a system whereby the activated system is in primary control of the vehicle – automated driving).

In this context, “lost cargo” is considered as an unplanned event requiring a transition demand – the transfer of the driving task from the system to the human driver. More specifically, lost cargo falls under the category of an “imminent collision risk” – a situation or an event which leads to a collision of the vehicle with another road user or an obstacle which cannot be avoided by a braking demand with less than $5m/s^2$. Thereby, the system will perform emergency maneuver (braking demand higher than $5m/s^2$) in case the vehicle faces an imminent collision risk, aiming to avoid or mitigate the collision.

UN regulation R157 (“R157”) sets the key system requirements to permit automated driving at speeds up to 130 km/h. The ALKS feature is already integrated into Level 2 systems according to SAE definitions, although R157 does not specify the level of automation per these definitions. For the purposes of this document, it is assumed that future Level 2 automated systems (and above) should satisfy the requirements of the lost cargo use case, for travelling speeds of 130 km/h.

However, identifying lost cargo and performing the appropriate driving maneuver can be a daunting and challenging task for automated driving systems. The aim of this white paper is to describe these challenges and potential solutions for this specific use case.

02 **CHALLENGE**

I. **BACKGROUND**

Detection of lost cargo is considered among the most challenging tasks of automated driving systems. The electromagnetic signal returning from an often small, low-reflectivity object is very low, resulting in a marginal Signal-to-Noise-Ratio (SNR). Furthermore, R157 requires detection of such objects in vehicles travelling at speeds up to 130 km/h which translates to long detection range (due to long braking distance).

Long detection range further intensifies the problem of marginal SNR of such objects and poses additional difficulty, requiring high resolution. The detection range of the automated driving sensing system is the distance at which the system can reliably recognize a target and generate a control signal accordingly. This range also considers the deterioration of components of the sensing system due to its usage throughout the vehicle's lifetime. Thus, detection range of a sensing system is compounded by a chain of degradation factors such as lighting and weather conditions and perception algorithms.

It is not enough to retrieve a signal from the obstacle, but rather be able to decide – taking all degradation factors into account – whether the obstacle possesses imminent collision risk, or not, and it needs to do so reliably. 'Reliably' in this context means two different parameters, which are both necessary:

1. **Confidence** – What is the confidence of this individual detection (signal)? What is the likelihood of a mistake?

2. **Repeatability** – Given the exact same scenario and conditions, what is the likelihood of the system providing exactly a similar answer again and again?

II. **REQUIREMENTS**

A sensing system used to detect obstacles with potential imminent collision risk must have the following characteristics:

1. Sufficient detection range to meet the R157 requirements (see Table 1).

2. Work with minimal degradation in adverse weather and poor lighting conditions.

3. Operate with minimal degradation in different driving conditions.

4. Resolution (or any other method) that reliably provides an estimation to the object's size (hence assisting in deciding whether the obstacle poses an imminent collision risk or not).

5. Reliable indication.

A. **Definitions and KPIs**

- A passable object is such an object that may be driven over without causing an unreasonable risk to the vehicle occupants or other road users, regardless of whether the tyre of the ego vehicle comes in contact with the object or not.
- The system needs to avoid a collision with a road user or an object fully or partially blocking the lane up to the maximum specified speed of the system with the following objects at least:
- *A stationary passenger car target.*
- *A stationary powered two-wheeler target.*
- *A stationary pedestrian target.*
- *A pedestrian target crossing the lane with a speed of 5 km/h for speeds of the ALKS vehicle up to 60km/h.*
- *A target representing a blocked lane.*
- *A target partially within the lane.*
- *Multiple consecutive obstacles blocking the lane (e.g. in the following order: ALKS vehicle - PTW - car).*
- *On a curved section of road.*

Please note that R157 does not define the size of the objects/targets nor definition of recognizing such entities. These are based only on widely accepted industry KPIs.

B. **Industry Common KPIs**

Customer requirements vary and are usually not public but provided in RFIs, RFQs or technical discussions. However, the below KPIs are widely agreed upon and are considered industry norms:

- Passable object height: approximately 15cm.
- Passable object width: approximately 40cm.
- Minimal number of pixels to enable classification as a passable object: 6x4 (HxV).
- Operate in all weather conditions (fog, rain, dust, humidity, snow, etc.).
- Operate in all lighting conditions.
- *Some degradation is allowed in adverse weather and lighting conditions as long as:*
  - *The system's performance is reduced according to these new conditions and*
  - *The driver is notified of this degradation.*
  - *Operate in all driving scenarios (glare from oncoming vehicles, tunnels).*

C. **Detection Range**

The increase in the maximum regulated speed from 60 km/h to 130 km/h necessitates longer detection ranges to confidently detect objects at longer distances up to 150 meters. The range is calculated based on a typical reaction time, a deceleration rate, and common road and tire conditions (such as non-extremely slippery conditions). It does not include other parameters which may affect detection range such as lighting and adverse weather conditions.

The forward detection range is measured from the foremost point of the vehicle:

- At least 46 meters for a specified maximum speed of 60 km/h.
- For speeds above 60 km/h, the minimum values correspond to Table 1, based on a deceleration of $5 m/s^2$.
- For speeds not mentioned in Table 1, linear interpolation should be applied.

Table 1: Forward detection range as a function of driving velocity

Specified maximum speed [km/h]	Minimum forward detection range* [m]
60	46
70	50
80	60
90	75
100	90
110	110
120	130
130	150

* Based on a deceleration of $5 m/s^2$

Achieving the minimum forward detection range and vehicle deceleration of $5 m/s^2$ may not be possible under all conditions (e.g. on slippery roads). The system must implement control strategies to adjust its maximum speed based on the actual detection range and the real deceleration capability.

D. **Environmental Conditions**

Environmental conditions refer to the compound state of lighting and weather conditions which may affect the detection performance of a sensing system. For example, low-light conditions such as night, dusk, or dawn, or to the other end, extreme light conditions such as direct sunlight, can significantly impact performance. Weather conditions are commonly divided into light conditions, in which the sensing system is almost not affected, and to adverse conditions which heavily affect (or completely obstruct) the system's detection capabilities. Weather phenomena include rain, snow, hail, dust, fog, smog, and more.

Furthermore, section 7.1.3 of R157 states the following: "The ALKS shall implement strategies to detect and compensate for environmental conditions that reduce the detection range, e.g. prevent enabling the system, disabling the system and transferring the control back to the driver, reducing the speed when visibility is too low." Thus, a sensing system is not only expected to be able to detect in varying environmental conditions, but also to be capable of detecting such conditions and act accordingly if the performance is expected to degrade.

E. **Industry Common KPIs**

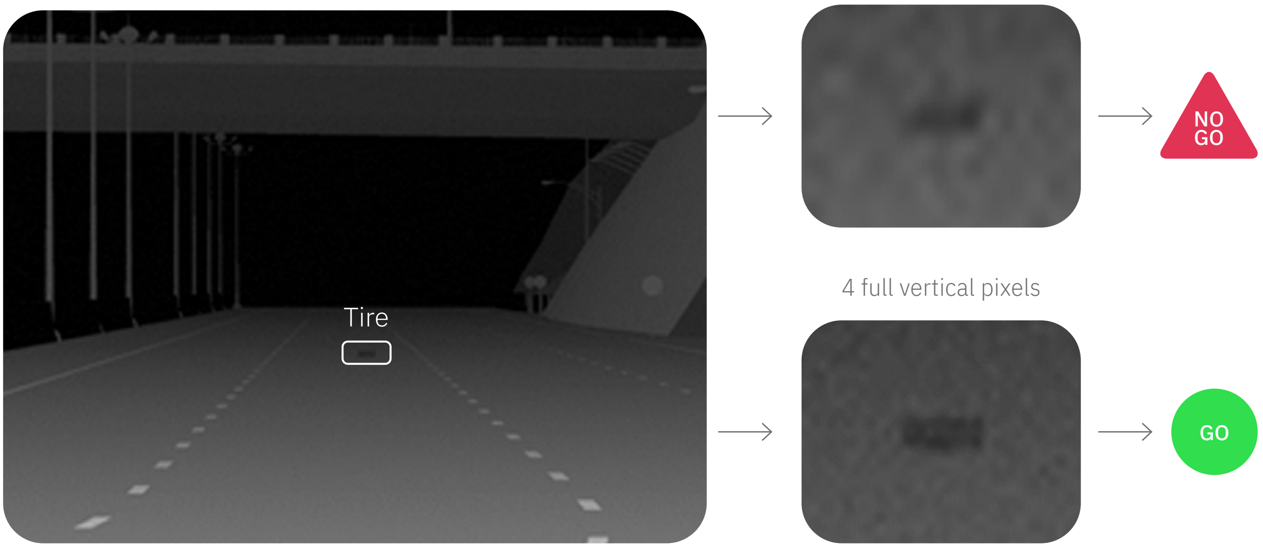
Driving conditions refer to the road's environment (e.g. road geometry ahead, lane markings) and the dynamics of traffic:

- Across the full width of its own traffic lane, the full width of the traffic lanes immediately to its left and to its right, up to the limit of the forward detection range.
- Monitor along the full length of the vehicle and up to the limit of the lateral detection range.

F. **Angular Resolution**

Angular resolution is a key parameter directly affecting the ability to detect and to accurately estimate object's size. The higher the resolution, the smaller the fraction of the Field-of-View (FoV) a pixel captures. For a given object, finer resolution means potential coverage of more pixels, hence providing a finer size estimation. See Figure 1 for the effect of angular resolution on size estimation.

Figure 1: 15x40cm tire on the road at 150m



The system's angular resolution affects multiple parameters. First and foremost, higher resolution increases the detection capability of the system. If an object is composed of more pixels, then the likelihood of that object being detected increases (fewer pixels may be viewed as noise, and it will take a few frames to validate that it is indeed an object). A higher confidence in object detection also implies higher reliability and thus more confidence in the detection. Further, an object comprised of more pixels will have a lower error in size estimation. In higher resolution, each pixel covers a smaller area, thus the impact of a few pixels on the estimated size of the object is minimized.

In low-reflectivity objects, contrast from the background is very limited, and thus more pixels are needed to "stand out" and provide reliable detection. Again, higher resolution increases the likelihood of this scenario. Finally, objects are almost never perfectly aligned with the pixel FoV ("grid"), hence it is expected that the object may also have a few pixels with partial pixel coverage. Meaning, that the object only covers a part of the pixel. Such partial coverage that has a lower signal is less likely to provide detection. Thus, higher resolution provides more "fully covered" pixels and some with partial coverage, again increasing the likelihood of this object to be detected.

For the following analysis, we shall assume parameters taken from R157 and some which are industry KPIs (see section 2.2.2). We shall assume an object 15cm high which needs to be detected at 150m and declare whether it is passable or not. This scenario is depicted in Figure 2.

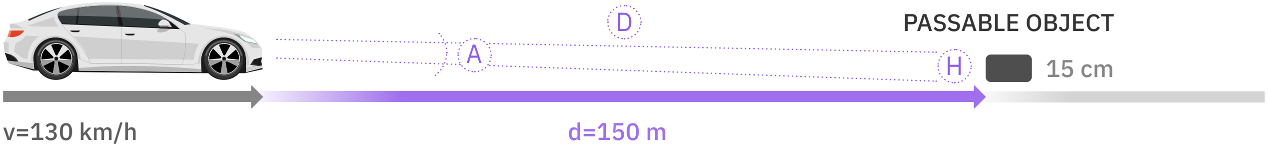


Figure 2: Lost cargo typical use case

Vertical view angle (a) = tan-1 [Object Height (h) / Distance (d)] → a = tan-1 [0.15 / 150] = 0.05°.

This means that a 15cm high object covers 0.05° vertical view angle ("coverage"). Thus, the required resolution (r) is defined by:

Vertical angular resolution (r) = Vertical view angle (a) / Minimal number of vertical pixels (p) →

r = 0.05° / 4 = 0.0125° / pixel.

Thus, a vertical resolution of 0.0125° / pixel is the minimum required to enable detection of passable objects at a distance of 150 meters (which is required at travelling speed of 130 km/h).

Please note that this analysis implies perfect alignment between pixel grid and the object in the FoV. As discussed earlier, it is almost certain that this is not the case most of the time; even finer resolution may be required. In the case where pixels and object are not fully aligned in FoV, then we have 5 pixels (3 full coverage and 2 partial coverage). Therefore, 0.01° / pixel vertical angular resolution is preferred.

G. **Other**

The effects of wear and aging should not diminish the sensing system's performance below the minimum required values throughout the system's lifetime.

03 SENSING MODALITIES

Automated driving systems require a variety of sub-systems to accomplish their major tasks; path planning and perception. Path planning sub-systems are used to determine the vehicle's accurate location in absolute terms (i.e., coordinates) and relative to the road's environment (for example, the specific lane or position within the lane). These sub-systems also provide information on the vehicle's movement and inertia. Such sub-systems include GPS (which provides absolute positioning) and inertial sensors such as accelerometers and gyroscopes (for movement and inertia). These sub-systems are outside the scope of this analysis, as the functionalities they fulfill are very different from the perception sensors, which are the focus of this analysis.

I. PERCEPTION REQUIREMENTS

Perception sensors are crucial for the safe operation of automated driving, with requirements stemming from the necessity to comprehensively understand the road and its users. Essential attributes for perception sensors include:

- Detecting all possible obstacles, ranging from small (like tire debris) to very large (such as an overturned truck), and across distances from very short (below 1m) to long (150m and beyond).
- Recognizing the drivable area, i.e., where the car is allowed to drive, and positioning the vehicle in relation to the road and other users.
- Detecting road users – including pedestrians, vehicles, motorcycles, bicycles, and trucks – for movement prediction and driving path assessment to prevent collisions.
- Identifying, classifying, and understanding road infrastructure, such as road signs, traffic lights, tunnels, and guardrails, essential for navigation and maneuver execution.
- Assessing the vehicle's self-driving parameters (also known as ego-motion), crucial for comparing with the planned driving path and identifying potential risks concerning other road users.

Sensor availability is another crucial factor. Sensors must function flawlessly in the vehicle's operational environments and be fully functional at all times. Therefore, sensors should be effective in various driving scenarios (e.g., highways, country roads, urban areas, tunnels, traffic jams, construction zones, etc.) and able to cope with new and unfamiliar situations. Additionally, sensors must operate in all lighting and weather conditions (including night, rain, fog, snow, dust storm, dusk/dawn, and glare). Finally, sensors must also assign confidence levels to their outputs. This implies that sensors are required to indicate the reliability of the data provided in comparison to a certain ground truth or expected performance level, especially under adverse weather conditions. Thus, sensors are required to provide a confidence value to each estimated parameter they output (for example, using false alarm rate (FAR) and true positive rate (TPR) KPIs, standard deviations, etc.).

The information provided from all sensors is processed using a software module called Sensor Fusion. Decisions on sensor selection, types, models, placement, data integration, and more, are influenced by factors including:

- Cost vs. Performance – Additional sensing modalities provide more information but cost more. The overall cost includes the sensor's price, the amortization of its development plan and testing, and vehicle integration.
- Decision making process – Roles and ranking of different sensor types for each driving function and how to resolve when disparate data is received.
- Functional Safety (FuSa), Failure & Recovery – The replaceability of sensors in case of failure, the impact of sensor failure on system decisions, and the minimum viable sensing required for autonomous driving in various scenarios.

Typically, automated driving systems incorporate different combinations of sensing modalities. The most used are visible cameras, radar, and ultrasonic sensors. With the advancement of driving functionalities, LiDAR is also added, creating a system that includes multiple cameras (front, side, fisheye, etc.), radars (long range and mid-range), ultrasonic sensors (on the front and back bumpers) and LiDAR. The cameras are synchronized with the radar (and LiDAR if exists) to provide localization, object detection, and environment modeling. Color images from the camera are commonly fused with the 3D point cloud of the LiDAR.

The sensor fusion model leverages the strengths of each modality and compensates for the disadvantages of others. For example, radar’s inherent range and velocity estimation offsets the limitations of such capabilities in standard cameras. Conversely, the high resolution and image processing capabilities of cameras facilitate color recognition and detailed imagery, leading to effective sign recognition and the classification of road users, among other tasks, thus mitigating the radar’s lower resolution.

In practice, sensor fusion systems commonly employ frame-to-frame detection of targets, complemented by subsequent data association, fusion, and tracking. Each sensor performs object detection independently, utilizing 3D processing techniques. To integrate data from each sensor, a hierarchical data fusion approach is employed.

II. LANDSCAPE ANALYSIS

A. Radar

Radar stands for Radio Detection and Ranging. This technology dates back to the late 19th century but was mainly adopted with the introduction of air-defense surveillance systems in WWII. Radar mainly operates in the microwave part of the electromagnetic spectrum (W Band, which is ~77GHz (between 74-79GHz for long-range detection), but also in 24GHz (short-range detection)). It sends out electromagnetic waves (thereby being active sensing) which are reflected from targets and detected by the radar system.

The system provides distance and direction to a target (thus 3-dimensional) as well as direct measurement of its dynamic parameters (such as velocity and acceleration) through Doppler shift measurements. Direct velocity measurement is very important for object detection and classification. The technology excels in harsh environmental conditions such as low light, bad weather, and extreme temperatures. However, the reflected signals are highly dependent on the object's material and its ability to reflect or absorb microwave frequencies, and thus, metal objects reflect strong signals, thereby producing a false sense of a larger object, whereas non-metal objects are almost undetectable and are often missed (false negative). Furthermore, their low resolution and vulnerability to stationary obstacles (difficult to differentiate between different types) and to crossing traffic (no forward/backward movement, thus doppler effect is only due to ego-motion) often results in providing insufficient information. Also, there is no semantic information.

The first automotive radar was introduced by Mercedes-Benz in 1998 for Automatic Cruise Control (ACC). It is considered a mature and relatively cheap technology, due to many generations since being first introduced. Today, radars are used in multiple applications and are sub-divided mainly by detection ranges. Three major types of radars:

- Short Range Radar (SRR) – Detection of objects at close distances, 0.2m up to 30m for blind spot detection (BSD), cut-in scenarios, pedestrian detection and warning, and parking assistance.
- Medium Range Radar (MRR) – Detection of objects at medium distances, up to ~100m for cross-traffic alert (FCTA for front and RCTA for rear), and rear collision warning (RCW), etc.
- Long Range Radar (LRR) – Detection of long-distance objects, up to ~200m for ACC and LKA.

The most advanced technology today is known as imaging radar. The term refers to the higher resolution of the sensor. The drawback is its computational resources.

B. **Camera**

Camera was the second sensor introduced for automotive purposes. Due to its role and significance, many types of cameras were developed since its introduction such as stereoscopic, fisheye (surround-view), thermal and high resolution. Most cameras operate in the visible spectrum, which makes them useful in daytime and in fine weather. Cameras excel at recognition of shape and color, such as road signs and separation lines, and therefore, are the primary sensor for all lane related functionalities such as lane keep assist (LKA) and lane departure warning (LDW), and speed monitoring such as adaptive cruise control (ACC). Cameras detect light reflected from targets by the sun or vehicle's headlights, and thus are heavily dependent on ambient light conditions.

Toyota introduced an automotive camera in 1991, and it was used while reverse-driving the vehicle. In 2007, Mobileye launched multiple systems for series production for LDW on GM and BMW vehicles and also a radar-camera fusion for ACC on Volvo vehicles. Today, cameras are considered to be the leading technology in ADAS due to their low price and perception capabilities which are similar to human perception. But cameras have two fundamental flaws:

- As they depend on external light, cameras are very vulnerable in harsh environments or completely non-functional (such as low light and adverse weather).
- Regular cameras also lack the ability to provide range (as the basic technology is only 2-dimensional). Indirect distance measurement is done using extensive computing resources.

C. **LiDAR**

LiDAR stands for Light Detection And Ranging and was originally used as imaging technology for geospatial sensing since the 1980s. It was first introduced in the automotive industry as part of the DARPA grand challenge in 2004 with LiDARs from Riegl and SICK. In 2005, Velodyne introduced its first LiDAR – the HDL-64E – in the second DARPA grand challenge. Since then, LiDARs have been used in most development fleets of autonomous vehicles.

LiDAR operates in the infrared (IR) part of the electromagnetic spectrum (i.e., between 850nm to 1,550nm). Like radar, it sends out pulses or continuous waves (thereby being active sensing), which are reflected from targets and detected by the LiDAR's detectors. It is especially good in low light conditions and reasonable in bad weather. Detection capability also relies on the sensor's sensitivity and system design.

The lower spectrum used by Near Infrared (NIR) LiDARs (850 – 1,100nm) is not considered as eye safe at high laser power levels; hence overall system performance is highly dependent upon the characteristics of the outgoing signals as well as the implemented safety mechanisms. The upper range of 1,500nm is considered eye-safe; hence it is often implemented in continuous wave (FMCW LiDARs), which provide direct velocity information (similar to radar). Nevertheless, with its eye-safety advantages, LiDARs which operate at 1,500nm are expensive as their photonics are non-silicon based and not scalable in a cost effective, high volume manufacturing process.

LiDAR provides distance and direction to a target (hence 3-dimensional) at a high resolution and a long range. Therefore, making it (currently) the primary sensor for lost cargo detection. LiDAR provides the best range and direction measurements of detected objects.

LiDAR is the most recent of the three major sensing technologies, thus it is the least mature, which is reflected by a higher unit price and hiccups in industrialization to mass-scale. But significant price reductions in the past years, especially those introduced with solid-state LiDARs, made it possible for vehicle manufacturers to integrate LiDARs as an important sensing technology in their AD projects.

The first automotive LiDAR for commercial purposes was introduced by Audi in its A8 at the EO 2017 using a Scala sensor by Valeo. LiDAR sensors are used for object detection and classification with accurate distance and high azimuth resolution and support functions such as pedestrian detection, AEB, collision avoidance, cut-in scenario, lane functionalities (LKA, LCA), and many more. In current automated driving systems, cameras and radars are usually considered the main sensors whereas LiDARs are mostly used as backup sensors for either camera or radar, for their primary functions.

As the technology is still immature, there are many types of LiDARs and different sub-technologies and implementation methods. Even KPIs are still being debated and argued. In terms of taxonomy, LiDARs are usually classified based on three major attributes: the wavelength they use, the way the field of view (FoV) is covered (Beam Steering), and the method they use to calculate the range to a target. Although, The most common LiDAR technologies are:

- Time of Flight (ToF) LiDAR – Uses laser pulses. These usually operate from short to medium-long ranges (150-200m) as they may have eye-safety concerns (and thus, are limited with light emitted).
- Frequency-Modulated Continuous Wave (FMCW) LiDAR – Uses a continuous laser beam. Long-range detection as they operate with practically no eye-safety limitations. Operate up to ~250m.
- Scanning LiDAR – Uses a rotating laser beam. Like ToF, these operate from short to medium-long distances.
- Flash LiDAR – Uses a single laser pulse, similar to camera flash. Flash LiDARs are used for short range, commonly up to 50m.

The main drawbacks of LiDAR systems are their cost and system complexity. They are far more expensive (absolute dollars and relative) with respect to cameras and radars. Consequently, their adoption was very slow. However, in recent years, significant reductions in LiDAR prices have made them a viable option for premium passenger cars and commercial fleets. LiDARs have not established a definitive niche where they outperform other sensors ,but small object detection (lost cargo) remains the sole use-case where LiDAR serves as the primary sensor. For all other automated driving functions, LiDARs remain supplementary sensors alongside cameras or radars.

D. **SEDAR**

SEDAR (Spectrum Enhanced Detection and Ranging) technology, first introduced by TriEye, is an innovative new sensor modality that has the potential to transform the automated driving sensor landscape. Unlike cameras, SEDAR uses an illumination unit which sends out pulses of light in the 1,338nm wavelength (SWIR) and the reflected signals are picked by a proprietary detector (thereby being active sensing). Similar to LiDARs which operate in the 1,500nm wavelength range, the Short-Wave Infrared (SWIR) spectrum is eye safe. However, unlike LiDARs, TriEye’s SWIR technology is silicon-based, enabling simpler photonics system, a high volume manufacturing platform, and considerably lower cost. Furthermore, SWIR delivers good SNR even in adverse weather conditions, and the reflected signals are generally less dependent on environmental and driving scenario conditions. SEDAR is designed in the SWIR wavelength range to offer the optimal combination of eye-safe electromagnetic range and good SNR, thereby balancing strong signals with relatively modest power consumption.

E. **Ultrasonic**

Ultrasonic sensors send out ultrasound waves (thereby being active sensing) and detect echoes to estimate the distance of nearby objects based on the time-of-flight principle. They operate effectively in all visibility conditions, but are designed for very short distances only (up to ~3m). However, compared to other sensors, ultrasonic sensors are somewhat limited. The speed of sound constrains their operation to very short distances and very slow movements. Additionally, they are prone to many false positives (i.e., detections that do not correspond to actual objects). While they can detect large objects at short range, they lack the capability to recognize or classify them. Their sole functionality is object detection at very short distances, which is used in parking assist systems and crash avoidance at slow speeds (such as detecting pedestrians at crosswalks and nearby vehicles at traffic lights).

Ultrasonic are not further elaborated upon in this document.

III. SENSOR HIGH-LEVEL COMPARISON

The main differences in capabilities of the sensors stem from three major attributes: (1) the frequency of the detected signal, (2) whether the technology is active (emits electromagnetic signals) or passive (only collects scattered signals), and (3) resolution. All major technical KPIs, such as weather resilience, detection range, accuracy, etc., are driven by these three attributes.

A. Resolution

Figure 3 presents the implications of the different electromagnetic spectrum bands on the (angular and range) resolution of perception sensors. The physical limitations (theoretical performance upper bounds) for the angular resolution as well as range resolution are given by the equations for the resolution and scattering of the electromagnetic wave as a function of the wavelength used and the diameter of the collector.

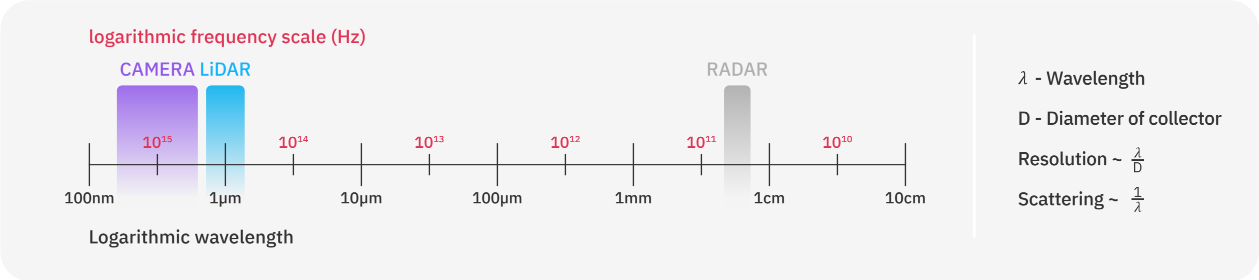


Figure 3: Implications of electromagnetic frequency

Camera angular resolution 0.01° at D=20cm

LiDAR angular resolution 0.03° at D=6cm

Radar angular resolution 1° at D=20cm

LiDAR range resolution 1mm

Radar range resolution 15cm

As presented in Figure 2 and further discussed in section 2.2.6, a 15cm high object at 150m is equivalent to 1mRAD which is ~0.05° angular resolution. This drives the required vertical angular resolution of the sensing system to be smaller than 0.0125° to ensure 4 entire pixels are available to detect and characterize an object. Obviously, if an OEM requirement for a passable object is less than 15cm, or if the requirement is to have more pixels for detection, then the required vertical angular resolution is even finer than 0.0125°. Further, since the object's positioning within the FoV is unknown, it could be that the object may not be exactly aligned with the pixels grid, which leads to partial coverage.

In the calculation provided earlier, a 15cm high object will most likely cover 5 vertical pixels, whereas the top and bottom pixels are partially covered, and the three central pixels are fully covered. Thus, it could be that a lost cargo may trigger more pixels than its actual height, or, to the other extreme, that the object is not detected in the pixels with partial coverage, leading to an estimated smaller (shorter) object. Thus, an ideal resolution would be even finer, such as 0.01°.

A.01 **Visible Cameras and SEDAR**

Both standard Off-The-Shelf (OTS) automotive cameras and TriEye's SEDAR platform with its >2MP sensor have a native 0.01° resolution, which satisfies the required angular resolution.

A.02 **LiDAR**

State of the art OTS LiDARs operate at 0.1° x 0.1°. A next-generation LiDAR system will have a fine angular resolution of 0.05° x 0.05°. Although impressive progress, it is not sufficient to meet the requirements of the lost cargo use case.

A.03 **Imaging Radar**

State of the art OTS imaging radars (the type of radar with highest angular resolution) operate at 0.5° x 0.5°. Future generation imaging radar systems target a fine angular resolution of 0.1° x 0.1°. Although represents impressive progress, it is far behind the requirements of the lost cargo use case.

The reason for this limitation is inherent within the radar technology and electromagnetic spectrum used. Due to the size of the aperture, imaging radars are restricted by limited antenna distances in the vehicle. Thus, the native resolution will not further improve (assuming vehicle dimensions are not going to dramatically increase).

A.04 **Discussion**

At ideal conditions, assuming zero system faults and assuming enough signal returning from an object, lost cargo would trigger a single pixel (vertical) in LiDAR and in imaging radar at a distance of 150m. If the object is split between two adjacent vertical pixels, and assuming enough signal is generated, the target would trigger two adjacent vertical pixels, and its height estimation would be greatly skewed. In the case of the LiDAR the estimated height would be 25cm, and in the case of imaging radar, 50cm.

Due to its relatively low resolution, imaging radars may not be able to determine whether the signal is in the ego lane or in the neighboring lane. It is a fundamental hurdle for the ego-vehicle as evasion maneuver or Emergency Maneuver may require diversion to a neighboring lane. A metal object on the side of the road can be interpreted as a non-passable object in the ego lane.

Further, imaging radars use real-time heuristics to enhance their information, but this requires immense computing power. The horizontal resolution of an imaging radar is typically 1°, and even with post-processing and high-resolution algorithms, it can only be slightly improved. Even with unlimited computing resources, this angular resolution is still marginal (or insufficient) for the numbers of horizontal pixels required for classification.

To conclude, the angular resolution of LiDARs and imaging radars may enable some detection of the object but not enough to declare whether the object is passable or not, hence does not meet the core requirement of UN regulation R157, i.e., to declare whether the object is passable or not. Using only LiDAR and imaging radar, one must always brake when an object is detected, even if passable. This will inevitably lead to 'phantom braking' and to a too high False Positive Rate (FPR). Because of this, LiDAR and imaging radar can only serve as a secondary sensors, whereas SEDAR can be used as a primary sensor for detecting objects and their distance.

B. **Signal and Environmental Conditions**

According to UN regulation R157, system providers/OEMs must declare the supported Operational Design Domain (ODD) and set its boundaries. The regulation does not require the system to operate in all lighting conditions, drive scenarios, or at all weather conditions. However, it does require the system to perform the following:

- Declare its Operational Design Domain (ODD) and its specific operating conditions (e.g., environmental, geographic, time-of-day, traffic, infrastructure, speed range, weather, and other conditions) within the boundaries fixed by the regulation under which the system is designed to operate without any intervention by the driver.
- Be able to continuously monitor the environment and estimate the current operating conditions.
- Be able to assess whether the current operating conditions are within the ODD or outside the ODD.
- If during operation there has been a change and the current operating conditions are now outside of the ODD, the system must alert the driver of the situation and perform a smooth handover to the driver without posing any risk.
- Furthermore, the system shall be able to disable the ALKS feature in cases where driving conditions are no longer within the boundaries of the defined ODD.

The latter two requirements imply that the system shall either be able to operate in adverse weather conditions, different lighting conditions, and all drive scenarios, or to be able to detect these in advance and hand the driving task back to the driver without posing any further risk. More specifically, the regulation states that:

- The activated system shall adapt the vehicle speed to infrastructural and environmental conditions (e.g., narrow curve radius, inclement weather, construction zones).
- The system must operate with a control strategy, which means a strategy to ensure robust and safe operation of the function(s) of "the system" in response to a specific set of ambient and/or operating conditions (such as road surface condition, traffic intensity, other road users, inclement weather conditions, etc.). This may include the automatic deactivation of a function or temporary performance restrictions (i.e., a reduction in the maximum operating speed, etc.).

The above regulation requirements imply that the sensing system must either operate in all conditions or be able to detect such conditions in real-time and avoid operation during such conditions.

B.01 **Visible Cameras**

The camera is the most vulnerable sensor when it comes to lighting conditions or adverse weather. A camera is a passive sensor, hence totally dependent upon external light. Cameras are thus, by design, limited in low light conditions and in other various conditions such as blinding light, transitions in lighting (high dynamic range scenarios) and adverse weather conditions such as rain, fog, and dust.

The attributes of a returned signal differ between different sensing modalities. In cameras, adding to its superb angular resolution, the main attribute is the color information. In all other sensors (LiDAR, imaging radar, and SEDAR), the returned signal is a compound of the illumination system and the sensor's capabilities. Cameras detect reflected sunlight and, if lighting conditions are sufficient (i.e., not total darkness or very thick fog), the detection range of cameras is practically infinite in terms of our analysis. Also, with sufficient sunlight, the color information is very good. As lighting conditions deteriorate, cameras become less capable and totally dependent on headlamps or other external lighting sources. Cameras are limited in the following conditions:

- Low light conditions such as night, dusk, and dawn – reliance upon headlamps or streetlights.
- Direct/blinding light – such as low-altitude sun or oncoming vehicle headlamps.
- Lighting transitions – such as when entering/exiting a tunnel, which require immediate and significant shutter adjustment.
- Adverse weather conditions – fog, rain, dust, humidity, snow, etc., leading to reduced/poor visibility.
- Water droplets on the windshield/camera lens – distort the image received by the sensor.
- Mirage on hot days – create phantom visual effects that confuse visual cameras.

On the other hand, perception algorithms of cameras are the closest to human perception, hence it is easier to declare whether the camera operates within its ODD, or not. Meaning, detecting adverse weather, water droplets, and other such cases, are best detected and declared using visible cameras. Although the performance of visible cameras is the least optimal under these conditions, they also possess the greatest capability to identify such scenarios (indicating they are outside of its ODD).

B.02 **LiDAR**

Although LiDAR is more immune than visible cameras to lighting conditions, various driving scenarios, and adverse weather, it still has its vulnerabilities. First and foremost, LiDAR's perception capabilities are sometimes incapable of identifying weather conditions with a reasonable level of confidence, which is crucial to determine whether it is operating within or outside its ODD. Also, adverse weather conditions deteriorate the LiDAR's performance as SNR decreases (light is scattered due to particles in the air such as water droplets, snow flakes ,dust, etc.).

As discussed, the signal in LiDAR depends on the illumination and the sensing capabilities of the reflected signal. With respect to illumination, the main factor driving performance is the frequency of operation and whether the electromagnetic band is considered eye safe or not. LiDARs are divided roughly into two groups:

- ~900nm – harmful to the eye if operated outside of a certain envelope. Such systems are limited in range and resolution by the flow of photons due to safety concerns.
- ~1500nm – considered eye safe and allows "unlimited" duty cycle. The practical limitation on the illumination intensity is derived from power usage and cooling needs rather than eye safety considerations.

Also divided into two:

- Pulsed LiDAR
- FMCW

Once the light hits the target, the amount of reflected (returning) photons is highly dependent on the object's reflectivity. Reflectivity of the target is based on its material type, color, and composition. Low reflecting materials such as tires return a very small number of photons, even for FMCW LiDARs which are considered to be the more powerful emitting LiDARs. Therefore, even state-of-the-art LiDARs have a limited detection range for small, low reflectivity objects such as tires. Even if theoretical calculations indicate that such an object can be detected at a long range, the combination of the resolution, object size and low reflectivity, may prove otherwise. A small object is smaller than a pixel at a long distance, and thus detection is not guaranteed. It also matters where the object falls within the FoV – if an object is split between neighboring pixels, then its overall signal is now split between 2 pixels and the signal per each pixel may now become even much lower.

In conclusion, the ability of LiDARs to detect small, low-reflectivity objects at long range is very low due to the very limited signal. This conclusion is even more prominent considering adverse weather. These conditions may dramatically reduce the detection capabilities of the LiDAR even for larger, more reflective targets. The advantage of LiDAR signals is the additional information provided, such as depth (range), reflectivity, and velocity (for FMCW LiDARs).

B.03 **Imaging Radar**

Imaging radars, like other types of radar, are immune to lighting conditions, driving scenarios, and adverse weather, performing consistently under such conditions without any degradation. They excel as the optimal sensor in these conditions, maintaining consistent performance without any degradation.

Similar to LiDARs, imaging radars provide additional information (attributes) for each reported signal. Specifically, like FMCW LiDARs, imaging radars are able to detect the object's velocity through a Doppler shift. Velocity estimation is most accurate when the object's movement aligns with the ego-vehicle's direction. It becomes less precise for vehicles moving tangentially (cross-traffic), and is least reliable for static objects. Consequently, in the case of lost cargo, where the object is static, velocity information is considerably restricted. Given the limited resolution of imaging radars and since non-moving objects have limited velocity information, it is challenging for radars to distinguish between these objects and other nearby static road infrastructure, potentially leading to their identification as a single object.

Generally speaking, the ability to distinguish between neighboring objects depends on the presence of velocity differences. Furthermore, reflected radar signals are significantly dependent on the object's material and its ability to reflect or absorb microwave frequency. Static metal objects such as soft drink cans or manhole covers reflect strong signals. Non-metal objects, on the other hand, exhibit low reflectivity (plastic cones, wooden boxes, etc.) and thus are almost undetectable in the microwave band (~20 GHz and ~77 GHz) due to their very low reflection/scattering cross-section. Therefore, small metal objects may even reflect stronger signals than much larger non-metal objects such as fallen wooden crates. Imaging radars have very limited information on materials – essentially divided into metals and the rest. As reflected radar signals are dependent upon object's relative velocity and its material type, classifying them into meaningful objects, such as passable or not, proves to be exceptionally challenging. Distinguishing between a manhole cover, cat's eye, and lost cargo is virtually impossible.

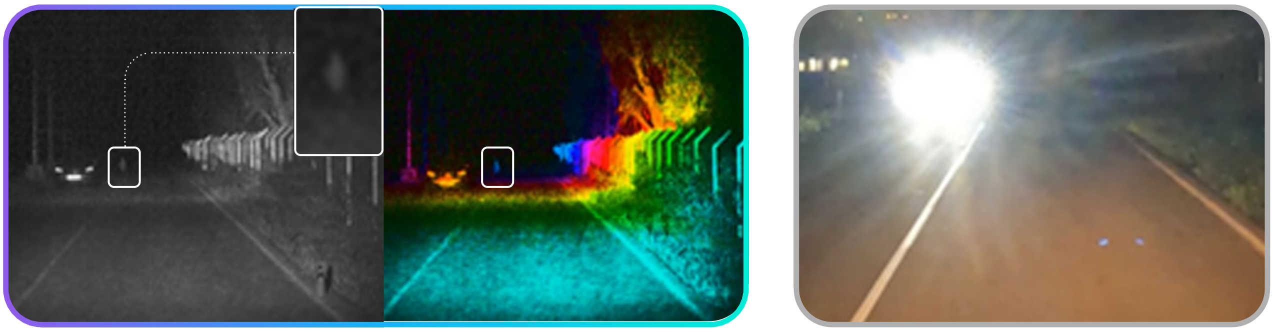
Furthermore, large metal objects (such as trucks) may introduce ambiguity and multipath effects, potentially saturating the scene. Consequently, even if lost cargo is detected, such a small static object might be disregarded in imaging radar systems (to ensure low FAR).

In conclusion, in terms of reflected signals, the ability of imaging radar to identify lost cargo and report such detection is notably limited.

B.04 **SEDAR**

Compared to LiDAR, SEDAR offers superior performance in adverse weather and is more resilient to lighting conditions and driving scenarios. It is more resistant to these conditions and has the capability to detect and classify them effectively. Similar to LiDARs and imaging radar, and unlike visible cameras, SEDAR uses an illumination unit which guarantees reflected signals regardless of lighting conditions. Furthermore, the specific wavelength (~1,350nm) ensures good SNR even in adverse weather and driving conditions and is immune to background noise from sunlight. The reflected signals, in general, are less influenced by environmental and scenario conditions.

Figure 4 and Figure 5 illustrate the extraordinary detection capabilities of the SEDAR system in challenging lighting conditions and different driving scenarios.



SEDAR™ 2D SEDAR™ 3D VISIBLE CAMERA

Figure 4: Pedestrian crossing at 150m behind a blinding vehicle

SEDAR™ 2D SEDAR™ 3D VISIBLE CAMERA

Figure 5: Small objects detection at 150m – Wooden pallets

B.05 **Discussion**

Reflected signals with semantic information from lost cargo are best detected using visible cameras, but only in fine weather and good lighting conditions. LiDAR and imaging radar are more influenced by other, non-controllable parameters, which may diminish the capability to detect and report the reflected signal. Under optimal conditions (fine weather and adequate external lighting), SEDAR and camera will detect lost cargo within 150m, even with very low reflectivity, at a very high confidence. LiDAR and imaging radar may detect such objects but with lower confidence (attributed to the low resolution), and only with sufficient reflectivity. Even then, the detected signal will be interpreted more as a warning signal ('something was detected') rather than an explicit classification of a passable object or not.

The capability to detect small objects with low reflectivity, also in poor lighting conditions and at a high resolution, is unique to SEDAR. No other sensing modality provides all three characteristics in a single sensing modality.

In conclusion, SEDAR offers the capabilities to function under any lighting conditions, driving scenarios, and adverse weather. An ideal automated driving sensing system, in this case, would include a visible camera to detect such conditions and imaging radar and SEDAR to operate and provide information in such conditions (even if performance is somewhat reduced). Relying upon a single sensing modality (imaging radar) to operate during such conditions does not meet the original requirement that the capabilities of the entire sensing system must either function in all conditions or be able to detect such conditions and avoid operating during them (be able to identify current conditions and assess them concerning the vehicle's predefined ODD). Safe operation always requires at least two independent and distinct sensing modalities to provide adequate information and serve as a backup to each other.

A summary of the major technical pros and cons of the sensing modalities is provided in Table 2.

Table 2: Performance of sensing modalities in different lighting and weather conditions

	Day	Night	HDR*	Light Weather Conditions**	Severe Weather Conditions**
Camera	+++	+	++	++	+
LiDAR	+++	+++	++	+++	+/++
Imaging Radar	+++	+++	++	+++	+++
SEDAR	+++	+++	+++	+++	++

+++ Excellent capability | ++ Reasonable capability | + Poor/non-existent capability

* HDR (High Dynamic Range): The ability to 'see' clearly a wide range of light/dark objects in a single frame. In Radar, HDR is defined by the ability to 'equally' detect a variety of objects/materials with different reflectivity.

** Weather Conditions include rain, snow, fog, dust, haze, direct sun, glare from oncoming vehicle and more

C. **Processing & Perception**

The last ‘link’ in the sensing ‘chain’ is the perception and sensor fusion. These are translated into a practical set of driving decisions, which the vehicle eventually incorporates into its decision-making algorithms. The capability and performance of the entire sensing system are eventually measured by the output and driving instructions provided by the sensor fusion subsystem. There are two critical factors determining the performance of these AI algorithms:

- The computing resources required for operation.
- Databases, training requirements, capabilities, and test scenarios needed to accurately classify objects.

The most comprehensive work and progress has been achieved on the data from visible cameras. There are a few reasons for that:

- It’s the most natural way to build and train the algorithms. The visible camera captures what human perception sees, making the work on these networks the easiest and most intuitive for engineers to build.
- The visible camera was the first sensor to utilize perception methods, hence there is valuable training data from many years.
- Visible cameras are the most common sensor in vehicles, making capturing training data is easiest.

Thus, a sensor modality that utilizes the networks built and operated for visible cameras (such as TriEye’s SEDAR) is the easiest to integrate and work with.

The lost cargo use-case involves detecting and recognizing any obstacle, which could be very small, at long distances. Unlike well-defined object classes such as cars or pedestrians, lost cargo obstacles pose a unique challenge due to their undefined nature, complicating detection, recognition (classification) and, obviously, the resulting vehicle’s response.

Detecting small, random objects on the road, known as 'lost cargo', and executing appropriate driving maneuvers is a challenging task for automated driving systems, especially when these objects are only a few centimeters in height and located up to 150 meters away.

Below are the key tasks for lost cargo perception:

- Detect the object on the road from a long distance, ensuring sufficient confidence.
- Determine the object’s range from the vehicle with sufficient accuracy.
- Integrate object data from all sensors and resolve conflicts – this is highly dependent on the precise alignment between the sensing modalities and various data types.
- Assess the unknown object’s size with high confidence, utilizing ranging and the number of pixels covered.
- Feed the decision-making algorithms with the findings: object size (and whether it’s passable or not), range, and associated confidence levels.

C.01 **Visible Camera**

Cameras typically employ predefined datasets to determine an object's range by correlating the object's characteristics to a predefined class. The size of the classified object in the FoV is utilized to estimate its range. However, a random object is undefined, therefore cameras cannot leverage prior information (datasets) for its classification and, consequently, to estimate its range. Moreover, classification becomes more challenging in low light conditions, thus amplifying the issue of unclassified objects and the difficulty in estimating their range.

C.02 **Imaging Radar**

As previously discussed, imaging radar requires massive digital processing to extract information finer than its native resolution. Moreover, to minimize FPR or the rate in which false detections/alerts are provided to the driver, substantial filtering methods and algorithms are deployed. These require additional computing resources, making the task of generating meaningful information from radars the most resource intensive.

Due to its low angular resolution, the separation of adjacent targets is possible mainly via velocity differences; usually, 0.1 m/s is enough for state-of-art radars. However, this argument does not apply to static objects. Neighboring points can no longer be clearly assigned to an object. Separation is only feasible with extensive heuristics, which again emphasizes the demand for computing resources.

Additionally, managing radar crosstalk (interference from an adjacent radar system) is complex and requires additional algorithms to address such cases.

In general, radar perception is less mature than that of visible cameras. There is one fundamental characteristic to keep in mind: radar has a limited number of receivers (~2000 elements), while a visible camera has millions of pixels, approximately 3 orders of magnitude more than a radar. Imaging radar, with its significantly lower resolution, is markedly affected by various materials, thereby complicating the integration of information from a visible camera.

In conclusion, imaging radar demands the highest computing resources but yields the least information.

C.03 **LiDAR**

Compared to imaging radar, LiDAR perception is more mature and easier to understand, yet it still falls behind visible cameras' capabilities. Currently, there is a lack of extensive experience and validated databases to prove robustness of classification algorithms. The computing resources required to analyze the 3D point cloud are not insignificant and results are heavily reliant on the training databases. Distinguishing a truck from a bus, for example, is straightforward for visible cameras, even at long ranges, but poses a greater challenge for LiDARs.

Regarding the lost cargo use case, LiDARs cannot estimate the size of small objects at long distances due to their limited resolution, and therefore, cannot reliably determine whether objects are passable or not.

C.04 **SEDAR**

The unique value proposition of the SEDAR sensing modality is that it offers an all-in-one solution. The system delivers camera-like resolution, adequate for classifying objects as passable or not, while maintaining consistent operation across day, night, and adverse weather conditions, providing synchronized 2D & 3D images without the need for active fusion. This latter attribute assures that the signal detected by the SEDAR system is accompanied by a reasonable range estimation, more than sufficient for the range estimation of lost cargo objects. These characteristics facilitate robust detection of lost cargo/small objects over long distances, as per ALKS regulation R157.

Even in daylight and fine weather conditions, perception, and classification as passable (or not), require reliable sensing, entailing high resolution, pixel information, and effective perception algorithms – all in a single solution.

The perception of SEDAR leverages visible camera networks, inheriting all the advantages of camera perception so it's easy to tell the difference between a truck and a bus. Additionally, any advancements made to these networks are immediately applicable to SEDAR. Therefore, SEDAR systems benefit from the most advanced perception networks without the need to invest resources in developing them.

C.05 **Sensor Fusion**

Even in daylight and perfect weather conditions, an automated driving system without SEDAR cannot directly measure an object’s range and its size. Performance-wise, information about the object’s range and its size is not immediately provided and is subject to a delay due to sensor fusion algorithms, a process known as the fusion challenge.

The automated driving system requires sensor fusion (merging data from several sensor modalities, such as image from camera and range from LiDAR), meaning it must employ sensor fusion algorithms to integrate data from different sensor modalities. This integration demands detection from both sensors, precise alignment, and even then, still introduces an additional layer of complexity, computing demands, latency, risk of false alarms, and extra development resources/training data.

Moreover, it involves combining different data types (such as the camera’s image and LiDAR’s point-cloud). Misalignment between the sensor modalities can lead to inaccurate estimations of an object’s attributes (such as size and shape) and can also completely compromise detection (raising the question: which system is correct?). For further objects ,even slight misalignment between the sensor modalities results in significant discrepancies in the object’s spatial positioning. Furthermore, under low light conditions, cameras will fail to detect objects at a large distance (150m), and then such fusion is completely unfeasible.

C.06 **Decision-Making Process Flow**

The decision-making process flow starts with sensing (detecting the object) and ends with a driving decision (such as maintaining current driving path, maneuvering, immediately braking, etc.). Figure 6 outlines the steps and considerations in this process.

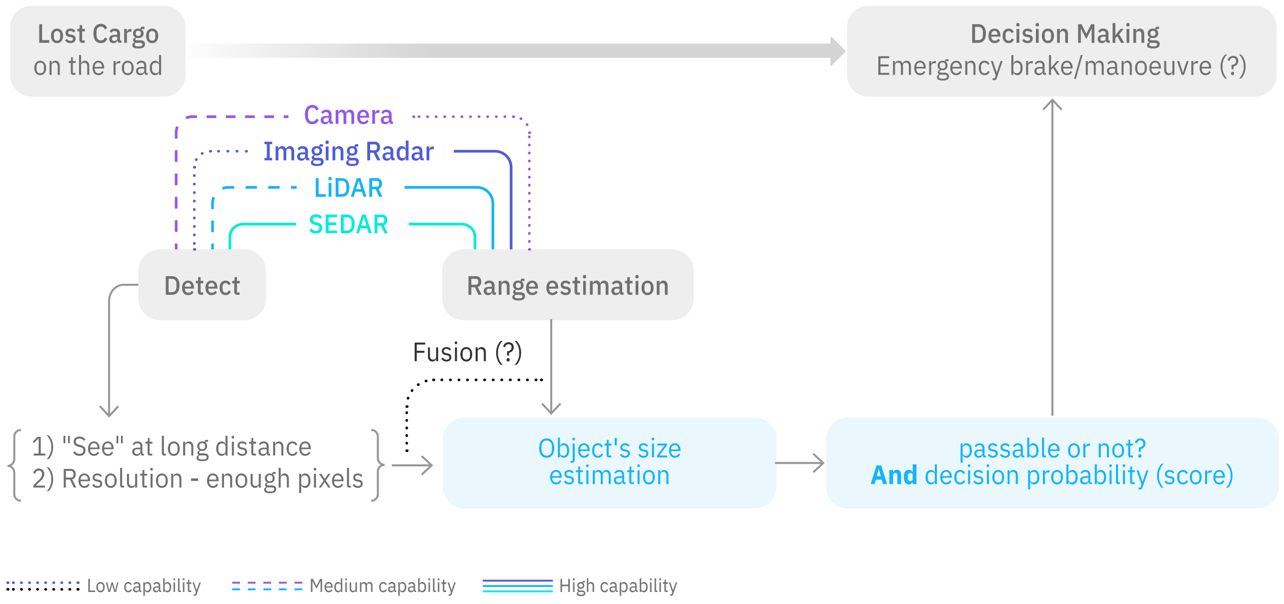


Figure 6: Sensing system decision-making process flow

In current automated driving systems, the object’s size cannot be directly estimated due to the limitations of the sensing system (as describedpreviously). Size is estimated only through indirect calculation of measurements coming from different sensors, which are assumed to be of the same object. During daytime and fine weather conditions, the primary indication and detection of objects stems from the camera system. It's unmatched resolution and ability to provide semantic information typically drives the detection and classification of objects.

But regular cameras cannot provide direct range estimation (note that 3D cameras are able to do so, but these are out of the scope of discussion as 3D cameras are not a standard sensing modality in automated driving systems). Cameras may indirectly estimate the object’s range through classification and temporal methods (measurements of consecutive frames over time). Nevertheless, lost cargo does not conform to a typical class, and one cannot provide accurate details in advance for such objects.

Lost cargo can represent any object. Thus, cameras are unable to provide a reliable range estimation for such diverse objects. Therefore, the information provided by the camera is fused with data from LiDAR or radar, assuming these successfully detected the object. Given their limited resolution, not every small object will be detected by these sensor modalities. Assuming accurate detection, the range estimation provided by the LiDAR and/or imaging radar, combined with the object’s size within the camera’s FoV, offers a method to calculate its actual physical size.

However, the above approach is limited in several ways. Firstly, cameras are practically incapable of ensuring reliable detection (or any detection at all) at night or under other challenging lighting conditions such as adverse weather, dusk, dawn, glare, etc. Thus, the outlined process is feasible only with sufficient lighting and in favorable weather conditions. Even then, it relies on the successful detection by at least LiDAR or imaging radar of small objects over long distances, which is rarely the in the lost cargo scenario. Finally, even if these conditions are met, effective fusion of information must occur, which is prone to errors even with slight misalignment in time or space between the different sensor modalities.

These considerations suggest why current operating automated systems lack such capabilities, even during daytime and fine weather conditions. Simply put, too many links in the sensing chain must function flawlessly to achieve the above desired outcome. Thus, even if all links operate successfully, the probability of such detection and estimation is generally low, which ultimately leads to the inoperability of this functionality at high speeds.

The SEDAR platform is a game-changer for a straightforward reason. It is the only sensor modality capable of providing all the necessary components to determine whether an object is passable or not, over long distances and under any given lighting and most weather conditions. It possesses the required resolution as well as long distance detection capabilities. SEDAR leverages its fully synchronized deterministic 2D & 3D images to provide object's size estimation, independent of lighting conditions and environmental impact.

D. **Summary**

There are many technical attributes that could be used to compare different sensor modalities, as well as models or brands within a specific sensor modality, such as between various stereo cameras or different imaging radars. Sadly, the industry lacks a universally agreed-upon set of KPIs or associated expected performance benchmarks. There isn't even a consensus on use-cases and associated performance requirements agreed upon between OEMs and regulators. Currently, each OEM selects a specific implementation of a sensor set and sensor fusion, then outlines a wish list of requirements which, in many cases is either:

- Too general, thus failing to highlight specific areas where certain sensors excel or have significant drawback, or
- Too specific, thereby tailored to a specific technology or a sensor brand rather than enabling a useful comparison.

Nevertheless, there are certain attributes that are commonly addressed while assessing automotive sensor modalities (described in section 3.2). Table 3 lists the physical attributes of the three main sensor modalities. In some cases, not all sensor modalities or different brands or models of a sensor modality are able to achieve these attributes (sacrificing performance over price or other non-technical KPIs), but the table outlines the general expectations from each modality.

Table 3: Key technical attributes for perception sensors

Attributes	Camera	LiDAR	Imaging radar
Environmental Perception	2D / 3D (if stereo)	3D*	3D and movement
Angular Resolution	0.01°	0.05°	1°
Color Perception	RGB	Reflectivity	None
Processing Requirements	Low (high if stereo)	Medium	High (low for other radars)
Sensing Technology	Passive	Active	Active
Perception Engine	Image recognition	Point Cloud	Spatial info
Spoofing / Phantom Objects	Vulnerable	Partially resilient	Vulnerable
Range Resolution	-	1cm	15cm

* Some LiDAR systems provide direct movement information as well (FMCW – see section 3.2.3).

Figure 7 quantifies the major KPIs and compares the current three major sensor modalities. Note that this comparison only provides some guidance, and there are challenges associated with such comparison. For example, achieving spatial resolution is particularly challenging with regular cameras (requiring massive computing power), whereas stereo cameras significantly enhance this aspect. Similarly, cost factors vary; regular cameras have become a commodity, even among low-cost brands, while stereo cameras remain exclusive to premium brands. Such differences also exist between regular radars and imaging radars.

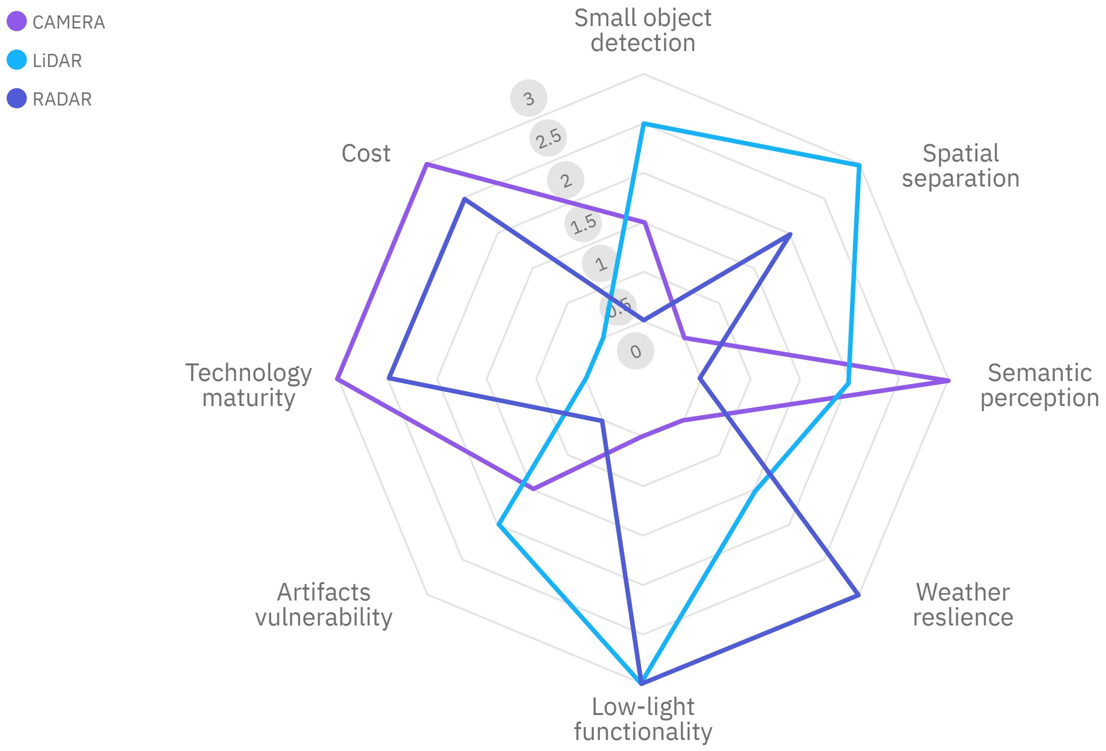


Figure 7: Major KPIs for sensor modality comparison

04 TAKEAWAYS

To comply with UN regulation R157, the entire sensing system must be able to properly detect, classify and respond to lost cargo objects. This process must be robust, exhibiting an extremely low false negative rate and a low false positive rate. Moreover, the system must function in all lighting conditions, driving scenarios, and weather conditions, and have the capability to detect such conditions and suspend operation if outside its ODD.

Breaking down the process flow, signal detection in LiDAR and imaging radar depends on uncontrollable parameters like the object's reflectivity, size, and movement, rendering their signal detection reliability for a small object at 150m insufficient for emergency maneuvers. The combined effect of system sensitivity, material type, object parameters, and the required certainty renders the 'SNR' inadequate for LiDAR and imaging radar in many scenarios. Conversely, combining SEDAR with a visible camera can achieve the SNR necessary for reliable object detection.

With object detection comes classification, which in most cases requires sufficient resolution. Although perception systems may vary in requirements, for the lost cargo use case, the resolution of LiDAR and imaging radar is too low to classify objects as passable or not. This makes both systems insufficient as primary sensors for this use case. The combination of SEDAR with a visible camera however, offer ample resolution for such classification.

Environmental conditions like lighting, driving scenarios, and adverse weather significantly affect camera performance, making it the most affected sensor. Yet, its capability to detect such conditions makes it an indispensable sensor, though not the primary one under these conditions. SEDAR, while not entirely immune to these conditions maintains adequate performance to serve as the primary sensor for this use case.

SEDAR's use of visible camera networks for perception also means it demands the least computing resources.

In summary, SEDAR stands out as the only sensor modality capable of providing the required performance to meet the conditions set by UN regulation R157.

Table 4: Summary of technical KPIs of sensing modalities

	Resolution	Lighting	Drive scenarios	Weather	Perception
Camera	+++	+	+	+	++
LiDAR	+	+++	+++	++	++
Imaging Radar	+	+++	+++	+++	+
SEDAR	+++	+++	+++	++	+++

+++ Excellent capability | ++ Reasonable capability | + Poor/non-existent capability

The complexity of use case requirements, challenging environmental conditions, and software/perception capabilities often leads current sensing modalities to fail at least one link in the perception chain. Only SEDAR meets all these requirements directly, eliminating the need for temporal and indirect calculations, and operated independently of sensor fusion or data from other sensing modalities.

Meeting UN regulation R157 is not just about detecting lost cargo at 150m. It also involves assessing whether the technology can classify if the object is passable or not, ensure consistent object detection, guarantee the reliability of such detection, and demonstrate the resilience of this detection to environmental conditions. Ultimately, the focus is not solely on detection but on the quality and robustness of the classification.

SEDAR is the only sensor modality capable of delivering the required performance and robustness to meet the conditions set by UN regulation R157 of the lost cargo use case.

APPENDIX: REFERENCES

1 M. Silverio; How to make a vehicle autonomous

2 What sensors are used in autonomous vehicles?

3 LiDAR vs Camera

4 The Use of RADAR Technology in Autonomous Vehicles

5 B. Goh; Autonomous Driving: Types of Sensors

6 N. Agnihotri; What are the sensors used in self-driving cars?

7 An Overview of Autonomous Sensors – LIDAR, RADAR, and Cameras

8 Sensors in Autonomous Vehicles

9 Three Sensor Types Drive Autonomous Vehicles

10 S. Campbell, N. Mahony, et.al., (2018). Sensor Technology in Autonomous Vehicles: A review. 1-4. 10.1109/ISSC.2018.8585340

11 H. A. Ignatious, H. El-Sayed, M. Khan. An overview of sensors in Autonomous Vehicles. Elsevier: 198 (2022) 736–741

SEEING BEYOND THE VISIBLE

TRIEYE

CONTACT US

info@trieye.tech
www.trieye.tech