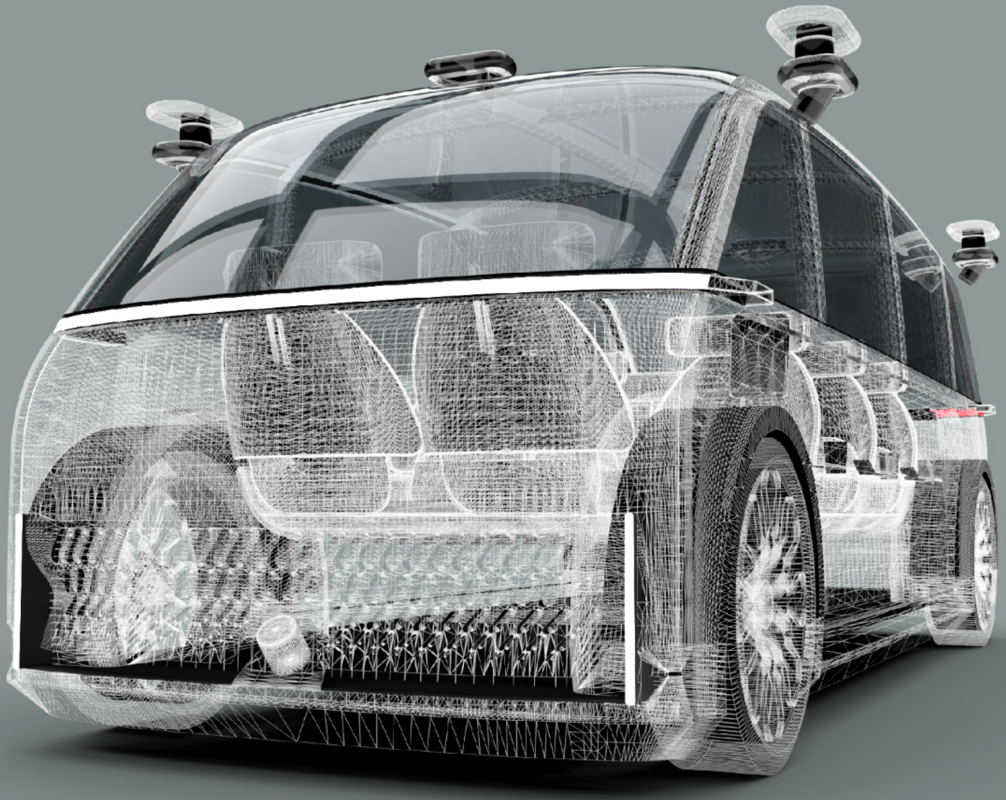
L4 Custom Design Guidelines



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Overview

This document is a guideline that consolidates practical design guides as a TIER IV standard for the development of vehicles compatible with Level 4 autonomous driving. This guideline consolidates a series of design and evaluation processes necessary for the development of autonomous vehicles.

1. Selection of Base Vehicle

Before embarking on the process of base vehicle selection and procurement, several preliminary steps must be accomplished. This ensures safety and functionality tailored to the Operational Design Domain (ODD) of the autonomous vehicle.

The first step in this process is defining the ODD. Understanding the specific environment where the autonomous vehicle will operate, such as urban roads, highways, or specific geofenced areas, is crucial to guide the rest of the design process.Next, use cases should be defined. This involves determining the main functions of the vehicle and the scenarios it will face during operation. For example, will the vehicle be used for transporting people, goods, or both? What conditions and situations must it handle?

Following the definition of ODD and use cases, the safety policy and requirements need to be established. These should be considered in relation to the ODD and use cases, and might include certification-based safety, safety argument, specific safety requirements, etc.

After these steps, the process of selecting and procuring the base vehicle can begin. There are primarily two patterns to consider. The first one is a vehicle designed and developed for autonomous driving. Since this vehicle is developed with the assumption of equipping autonomous driving (AD) software, it is already Drive-By-Wire ready, and it is sufficient to match the interface between the vehicle and the software. However, as the market size for autonomous vehicles is still small and mass production is not yet in place, there are issues in terms of cost, quality, and after-sales support.

The second one is a vehicle developed with manual driving in mind. Since this vehicle is not developed for autonomous driving, it is not Drive-By-Wire ready and needs modifications in various parts. However, the base vehicle's cost is lower, and it has the advantage of being superior in terms of quality.

Considering these two patterns, it is essential to select and procure the most suitable base vehicle by taking into account various factors. What you aim to achieve with the autonomous vehicle plays a significant role in this decision. The objectives could range from improving transport efficiency to offering advanced mobility solutions or even launching a new business model. These objectives will inherently influence the type of vehicle needed.

The types of vehicles available for procurement, such as buses, passenger cars, and others, also need to be considered. The choice of vehicle should align with the defined use cases and ODD. For instance, an autonomous bus might be suitable for public transportation within a geofenced area, while a passenger car might be ideal for a rideshare service.

The facilities you have at your disposal also influence this decision. For example, certain types of vehicles may require specific maintenance facilities or charging infrastructures. The feasibility of accommodating these needs within your current facility constraints should be factored into the decision-making process.

By considering all these elements, you can make an informed choice about which base vehicle is most appropriate for your autonomous vehicle project.

2. Electrical and Electronic Architecture (E/EA)

Autonomous vehicles require development centered on ADsoftware. Therefore, the vehicle needs to be a Software-Defined Vehicle (SDV). This chapter discusses the E/EA that makes SDV possible.

In autonomous vehicles, the AD software is central and issues instructions. Therefore, it is necessary for the software to be able to issue control instructions to all parts of the vehicle and to obtain data from all sensors mounted on the vehicle. On the other hand, the interfaces for sensors and control targets mounted on the vehicle vary. Figure 1 shows the general configuration of an autonomous vehicle. In this configuration, a Vehicle Control Unit (VCU) is provided to convert the output of the AD software (AD System in the figure) into vehicle-specific control signals. This allows the AD software to control and manage information from the vehicle through the VCU. The VCU, under the instructions from the AD software, controls each component mounted on the vehicle, such as the Electronic Braking System (EBS) and the Electronic Power Steering (EPS).

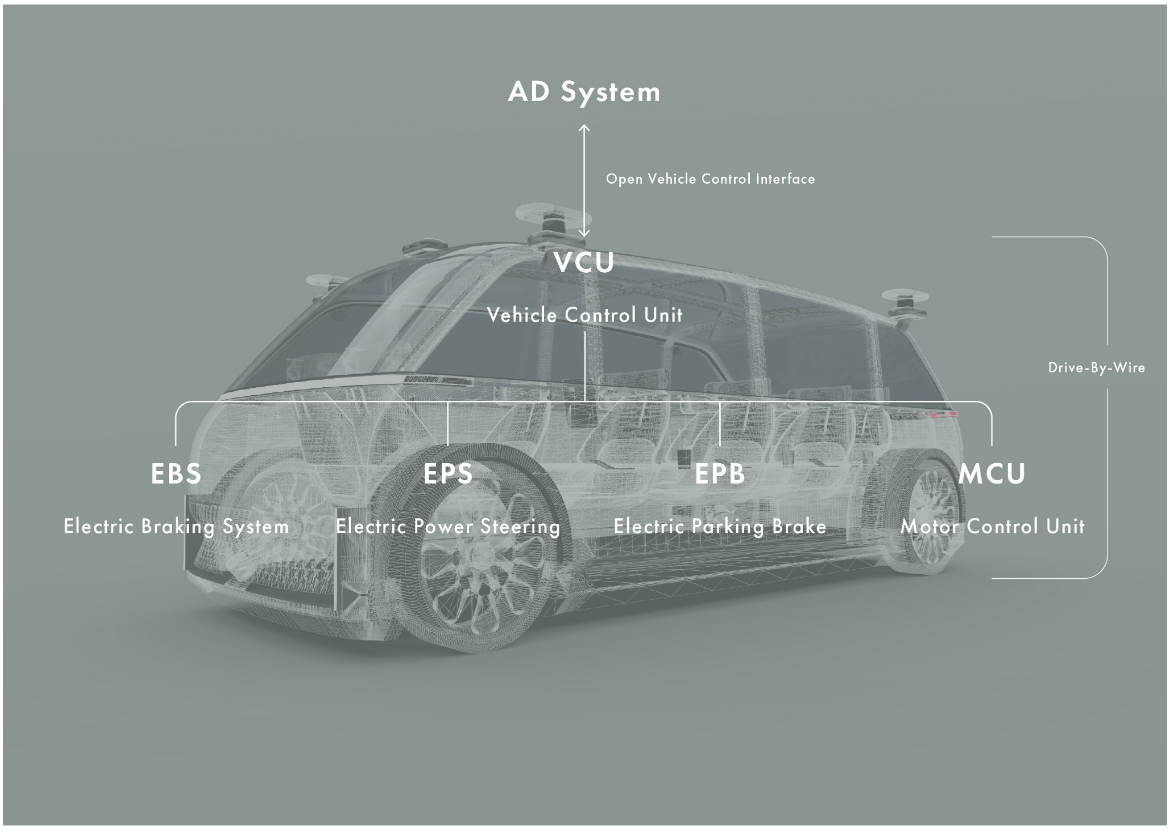


Figure 1 Configuration of autonomous vehicles

3. Drive-By-Wire

In this chapter, we will discuss the Drive-By-Wire necessary for autonomous vehicles.

3.1 Vehicle Customization

In this section, we discuss the vehicle modification methods required for Drive-By-Wire. In developing an autonomous vehicle, there are primarily three cases regarding the condition of the selected base vehicle.

The first case is when the VCU and interface as shown in Figure 1 are provided in advance, under the support of the OEM who developed and manufactured the vehicle. In this case, no modification to the vehicle is necessary, making it the easiest way to develop an autonomous vehicle.

The second case is when disclosure of internal vehicle information and interfaces of various components such as EBS and EPS is available, under the support of the OEM who developed and manufactured the vehicle or the supplier of the installed components. In this case, additional development of the VCU is required.

The third case is when there is no support from the OEM who developed and manufactured the vehicle, and the vehicle is a black box. In this case, replacement with controllable components and the addition of sensors such as vehicle speed sensors and steering angle sensors are required to control vehicle motion and to obtain vehicle information needed by the AD software.

3.2 Open Vehicle Control Interface

It is necessary to define the interface between the ADsoftware and the vehicle. This interface mainly consists of two parts: control passed from the AD software to the vehicle and vehicle relayed from the vehicle to the ADsoftware. Table 1 lists an exmaple of vehicle interface. This interface is just one example, and depending on the vehicle specifications, different interfaces may need to be prepared.

Category	Item	Side note
Control command	Acceleration	m/s2
	Brake	Not necessary if deceleration is possible with acceleration indication
	Steering	radius
	Blinker	
	Shift	
	Door	
	Wiper	
Vehicle status	Speed	
	Steering angle	
	Shift position	
	Blinker status	
	diag	

Table 1 Example of vehicle interface

3.3 Performance Requirements

Drive-By-Wire is an onboard computer control function that electrifies the drivetrain, such as brakes and steering, and enables actuation by AD functions. To drive safely within the driving area defined by the target ODD while meeting user needs, high responsiveness and vehicle motion detection accuracy are required in vehicle control processing. Therefore, to ensure a certain performance as an autonomous vehicle, it is necessary to define performance indicators between the AD software and Drive-By-Wire and develop accordingly.

Table 2 summarizes an example of performance requirements that AD software could require from Drive-By-Wire. These requirements are not meant to apply to all autonomous vehicles. They are tailored to a particular combination of vehicle base, ODD and safety design. In this case they are examples of requirements described by TIER IV to meet an AD system in target ODD.

Category	Requirements
Acceleration Control	The error between the target acceleration and the actual acceleration is within 10% in all vehicle speed ranges
	Dead time is within 0.2 second and time constant is within 0.6 second
Brake Control	The error between the target acceleration and the actual acceleration is within 10% in all vehicle speed ranges
	Dead time is within 0.2 second and time constant is within 0.6 second
Steering Control	The error between the target steering angle and the actual steering angle is within 5% in all vehicle speed ranges
	Dead time is within 0.1 second and time constant is within 0.5 second
Vehicle speed	The error between the true vehicle speed and the measured vehicle speed is within 3%
	Vehicle speed can be measured at a frequency of 50hz or higher.
	The lower limit of the vehicle speed measurement range is 0.1m/s2
Steering angle	The error between the true yaw rate and the calculated yaw rate with measured steering angle and vehicle speed is within 3%
	Steering angle can be measured at a frequency of 50hz or higher.

Table 2 Example performance requirements of Drive-By-Wire

3.4 Safety Requirements

For Level 4 autonomous vehicles, unlike Level 2, a level of safety equivalent to a human driver is required. The design concept of onboard systems in Level 2 vehicles, where the driver is responsible for driving, is based on fail-safe principles; if the system function fails during driving, the electronic control function (driving assistance) stops, and the driver is responsible for ensuring safety. On the other hand, in vehicles of Level 3 or above, where the system assumes driving responsibility, driver intervention cannot be expected to ensure safety during system function failure, thus a high level of reliability (safety) is required for the Minimum Risk Maneuver (MRM) to minimize risk in the absence of human intervention. Moreover, vehicles of Level 4 and above are operated without personnel who can substitute for driving, so an MRM function that can move to an open space on the side of the road to avoid obstructing the traffic of other road users after an emergency stop due to system failure is required. To meet these requirements, at a minimum, the modules used for deceleration control and lateral movement control and the sensor devices to ensure the reliability of fault diagnosis need to have redundant hardware and software modules to maintain functionality in case of failure. These core module groups of Level 4 vehicles are collectively referred to as Redundant Drive-By-Wire.

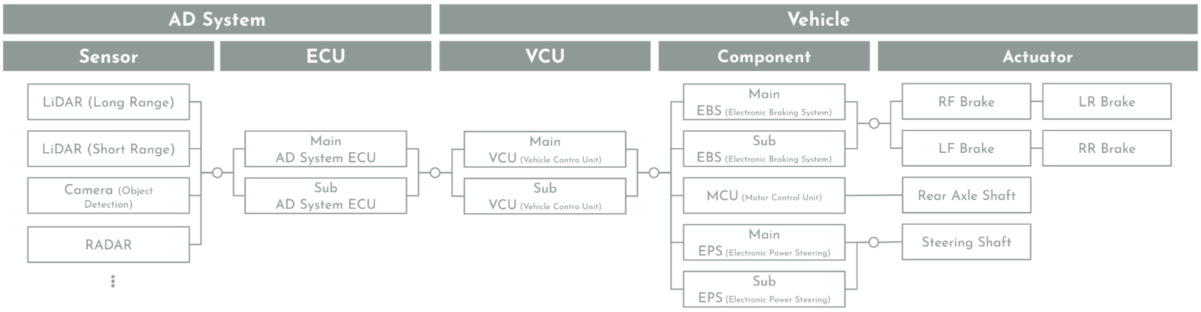


Figure 2 Redundant Drive-By-Wire

4. Sensor Configuration

This chapter discusses the design of the sensor configuration to be installed in autonomous vehicles.

4.1 Requirement Definition

In order to define the requirements for sensor placement, it is necessary to first define the ODD and identify the use cases within the ODD. By determining the use cases that autonomous vehicles should address, the requirements for perception functions and sensors can be defined. Figure 3 provides an example. By calculating the sensor requirements from the right turn use case, it can be determined at what distance ahead the oncoming vehicle needs to be recognized, considering the required travel time for the ego vehicle to cross the intersection and the assumed speed of the oncoming vehicle. The sensor requirements can then be defined based on the distance to be recognized and the specifications of the object detection algorithm to be employed.

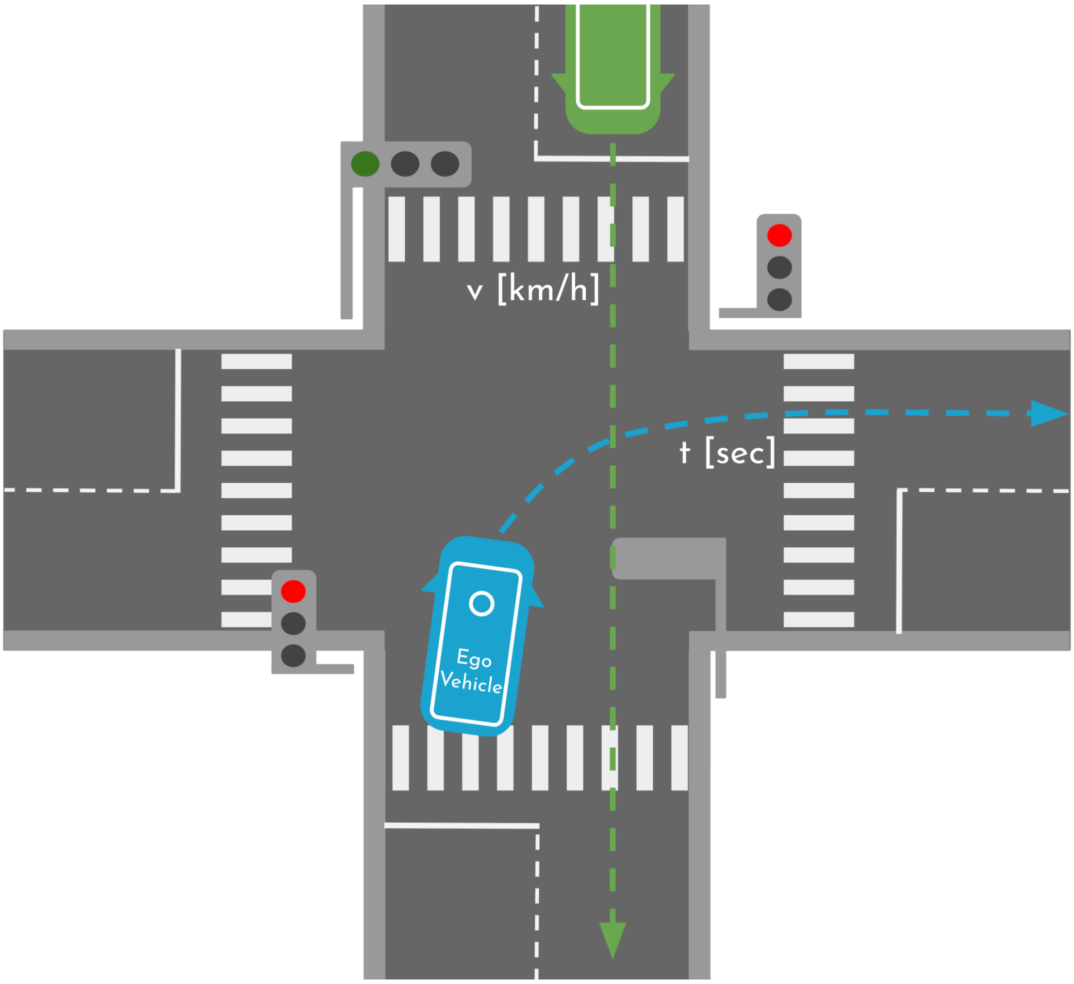


Figure 3 Example use case: right turn at an intersection

4.2 Design of Sensor Configuration

Consider sensor models and installation positions according to the requirements. One way of evaluation sensor position and sensor coverage, is by simulating sensors in a 3D environment. Figure 4 shows an example sensor simulation for sensor evaluation. By simulating the use cases that need to be addressed, the optimal sensor models and installation positions can be examined.

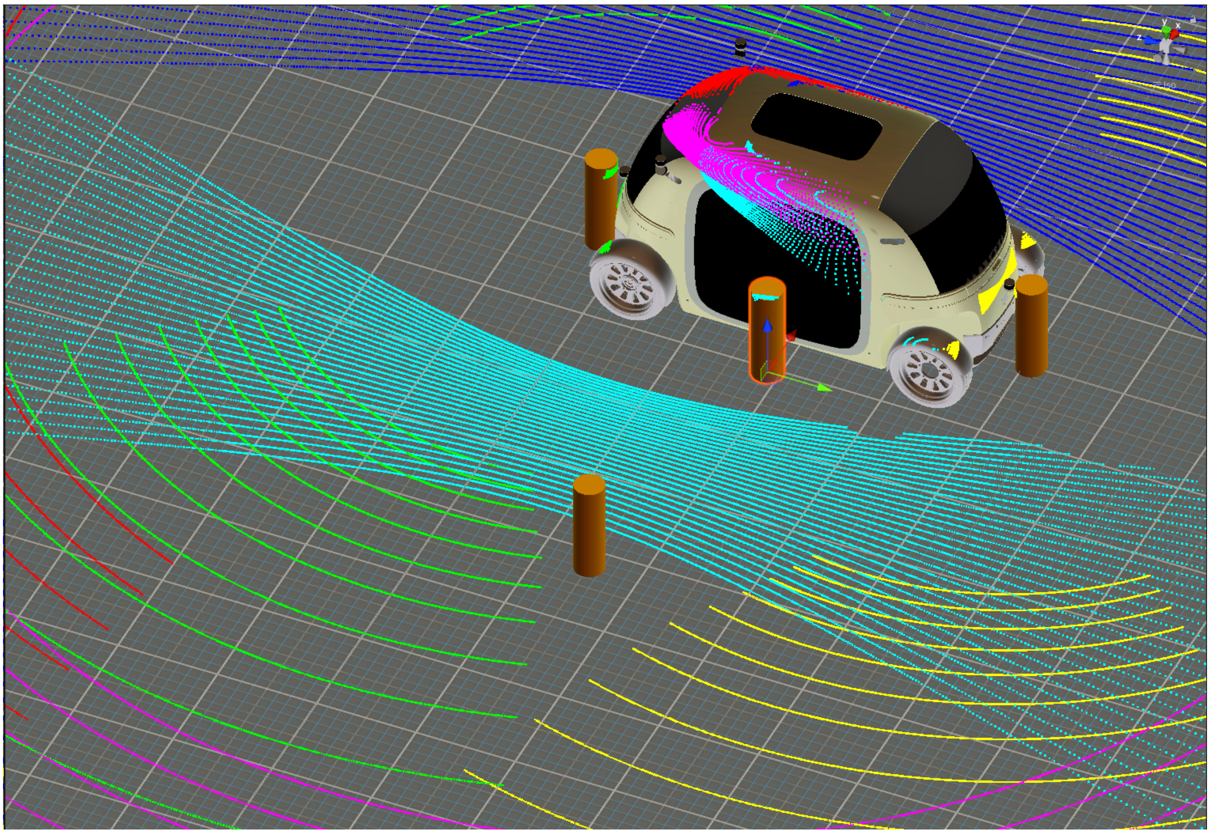


Figure 4 An example of sensor simulation for design sensor configuration

5. Autonomous Driving System Development

In this chapter, we will explain the general development process of an AD system.

5.1 Autonomous Driving Software Development

In the development of AD software, just like sensor placement, it is also important to start by defining the ODD and identifying the use cases within the ODD. Based on the use cases that need to be addressed, the requirements for the features of the AD software are defined, and the development of the functionalities is carried out. Additionally, alongside feature development, scenarios are created to evaluate the use cases that need to be fulfilled, enabling the verification of the functionalities.

5.2 ECU Design

As mentioned in the previous chapter, Level 4 autonomous vehicles require advanced safety measures, unlike Level 2. In the event of a system failure, the ADsystem must detect the failure and transition to a safe state within an adequate time frame. For ensuring safety in such cases of system function failure, Minimum Risk Maneuvers (MRMs) are determined based on the ODD and safety requirements. Here, we will discuss two representative examples of MRMs that should be implemented in the AD system: "Emergency Stop" and "Fail Operational."

Emergency Stop

The "Emergency Stop" MRM refers to stopping the vehicle with maximum deceleration without any steering operation. This MRM can be applicable in cases where such emergency stop behavior is acceptable. For example, in a use case of low-speed driving within a restricted private area, an emergency stop after detecting a failure can still ensure safety. Additionally, this MRM can be relatively low-cost to implement.

Fail Operational

The "Fail Operational" MRM involves moving the vehicle while performing steering operations to reach the nearest safe location and stop the vehicle. This MRM is typically needed in cases where availability is required. For example, in the case of Level 4 ADin a public road environment, after detecting a failure, the system needs to ensure safety while performing contingency actions. While this MRM provides greater flexibility in achieving the functionality, it can also be relatively costly to implement.

To enable the implementation of the two representative MRMs mentioned above in an ADsystem, it is necessary to achieve an ECU configuration that meets the following requirements:

	Emergency Stop	Fail Operational
ECU configuration requirements	● Failures must be detected ● After failure detection, it must be able to demand deceleration with the brake to VCU.	● Failures must be detected ● After failure detection, it must be able to demand deceleration with the brake to VCU. ● It must be able to operate appropriate MRM (minimum risk maneuver) on different failure levels ● Even if a primary ECU fails, a redundant ECU must be able to operate MRM.

Table 3 Example of requirements of ECUs

Figure 5 illustrates a representative example of ECU configuration that meets the requirements for both Emergency Stop and Fail Operational while achieving Lv4 autonomous driving. The configuration in the lower left provides a simple and cost-effective solution while enabling Emergency Stop. However, the range of Lv4 AD use cases that can be achieved is limited. As we move towards the upper right, the configuration becomes more complex, but it allows for improved safety, and availability, enabling a broader range of Lv4 AD use cases.

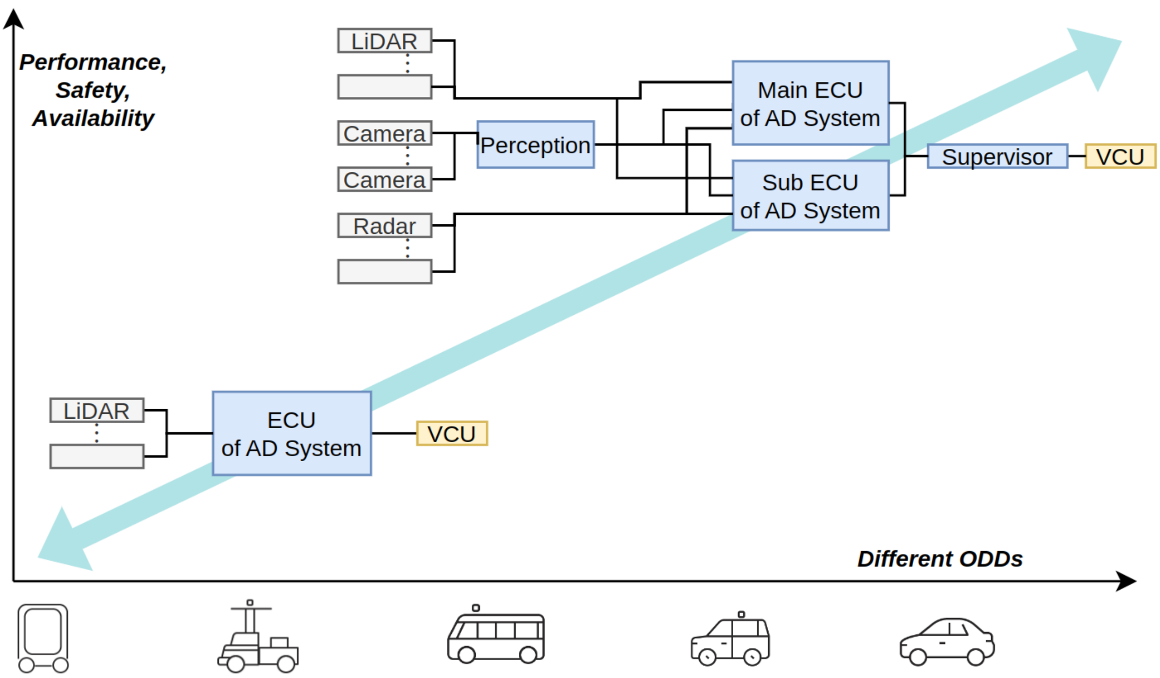


Figure5 Example ECU Configuration

6. Evaluation

In this chapter, we will explain the evaluation of autonomous vehicles. The evaluation process is divided into three categories: Drive-By-Wire evaluation, sensor evaluation, and AD software evaluation. We will now provide an explanation of each evaluation category.

Drive-By-Wire test

After the design and implementation of Drive-By-Wire (DBW) is completed, an evaluation is necessary to confirm that the vehicle can be used as an autonomous vehicle. For the evaluation of DBW, the following tests should be conducted in sequence:

Sensing Accuracy Test: This test involves verifying the accuracy of sensors such as vehicle speed sensors and steering angle sensors. It ensures that the vehicle's state can be accurately measured for subsequent tests. To verify the accuracy, reference measurements from other well-calibrated instruments are taken and treated as ground truth for comparison.

Accuracy Test of Each Vehicle Function: In this test, the accuracy of each vehicle function during ADis verified. The test involves inputting command values from the AD system and confirming if the output values align with the expected values. For example, if a torque command is inputted from the AD driving system, the resulting vehicle speed is measured and compared to the expected acceleration calculated by the ADsystem. Any discrepancies are identified and rectified.

These tests help ensure that the DBW system functions accurately and performs as intended during autonomous driving. Any deviations or errors discovered during the evaluation process can be addressed and resolved before the vehicle is used as an autonomous vehicle.

Sensor test

In order to meet the sensor performance requirements validated through simulation, the evaluation process begins with individual sensor performance and reliability assessments. This involves conducting tests to evaluate the performance and reliability of the sensors in isolation. Subsequently, the sensors are installed on the actual vehicle to acquire real-world data for further evaluation.

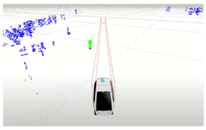
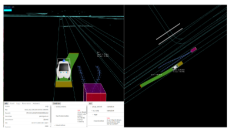
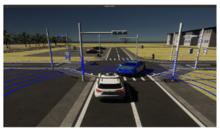
During the evaluation using real-world data, not only are the output results of the sensors assessed, but also the performance of the object detection algorithms is verified. This ensures that the sensors not only provide accurate output, but also demonstrate sufficient performance when integrated with the object detection algorithms.

By conducting these evaluations, both in simulated and real-world scenarios, the sensor performance can be thoroughly assessed and validated, providing confidence in their capabilities for use in the ADsystem.

The evaluation of autonomous driving software

After the design and implementation of the features required to achieve the use cases, it is necessary to evaluate and confirm whether the functionalities exhibit the desired behavior and can successfully achieve the use cases. Figure 6 provides a list of evaluation methods for this purpose. Each item to be validated requires the selection of the most appropriate evaluation method to conduct the assessment.

While conducting evaluations using real-world testing is the most reliable approach, it may not be feasible due to the time and cost involved. Therefore, it is advantageous to utilize simulators to achieve evaluations that balance both safety and efficiency.


	Driving Log Replayer	Scene Simulator for Path Planning	Scene Simulator for Autoware (AWSIM)	Real Vehicle Test
Sensing	✔		✔	✔
Localization	✔		✔	✔
Perception	✔	(✔)	✔	✔
Planning		✔	✔	✔
Control		(✔)	✔	✔

Figure 6 Example of evaluation methods

7. Case Study

7.1 Mini EV Bus

In this chapter, we will present a design case study of a mini electric vehicle (EV)bus. The base vehicle used for this case study is a mini EV bus, which was modified to make it compatible with autonomous driving. Figure 4 illustrates the system configuration that was added or customized to make the base mini EV bus autonomous driving-ready.

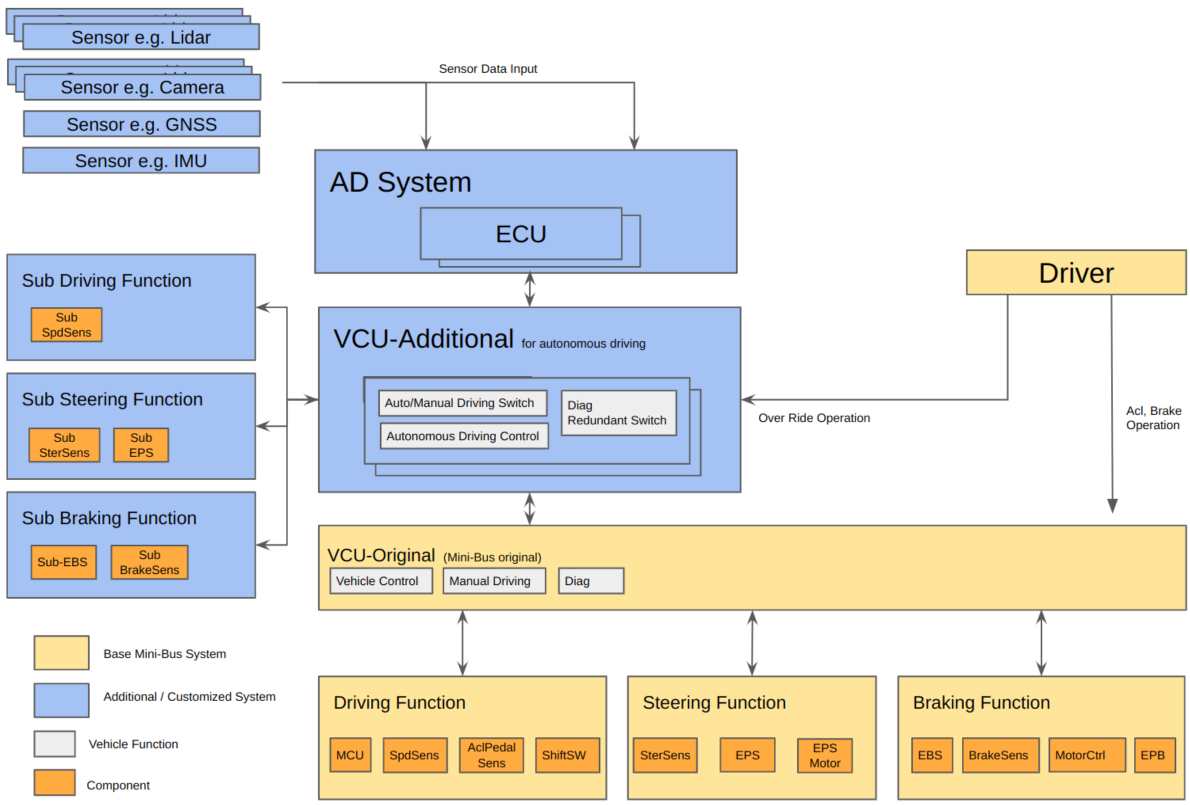


Figure 4 Architecture of mini EV bus

Below is a summary of the development example undertaken to meet safety requirements and use cases. Note that the actual development process involved various activities, and the most important thing for engineers is to design an AD system and EV system that strike the best balance while keeping the ODD and safety goals in mind.

Driving Funciton

As components that constitute the driving functions of the EV system, we consider a motor and motor controller (MCU), a vehicle speed sensor (SpdSens), an accelerator pedal sensor (AclPedalSens), and a shift switch (ShiftSW).

In the case where the only means of obtaining the vehicle speed in the base medium-sized EV bus is the speed sensor attached to the tires, a problem arises if the speed sensor malfunctions, as the current vehicle speed cannot be determined, and the intended AD operation cannot be achieved. In this configuration example, redundancy is achieved by adding another speed sensor (SubSpdSens) to mitigate such issues.

Steering Function

As components that constitute the steering functions of the EV system, we consider EPS (Electric Power Steering), EPS motor (EPS Motor), steering shaft, steering rod, and steering angle sensor (SterSens).

In the case where the only means of obtaining the steering angle in the base medium-sized EV bus is the steering angle sensor attached to the steering shaft, a problem arises if the steering angle sensor malfunctions, as the current steering angle cannot be determined, and the intended AD operation cannot be achieved. In this configuration example, redundancy is achieved by installing an additional steering angle sensor to ensure redundant steering angle acquisition.

Braking Function

As components that constitute the braking functions of the EV system, we consider the motor (regenerative) (MotorCtrl), EBS (Electronic Braking System), EPB (Electric Parking Brake), brake pedal sensor, brake master cylinder, vacuum pump, vehicle speed sensor, hydraulic sensor, and others.

In the case of the base medium-sized EV bus, the braking force sources are regenerative braking from the motor and EBA (Electro-Hydraulic Brake Assist). If the EBS malfunctions and the motor alone cannot generate sufficient braking force, the braking distance may be extended, making it difficult to come to a stop at a safe distance. In this configuration example, redundancy is achieved by installing a SubEBS to ensure redundant braking functionality.

VCU-Additional

The VCU (Vehicle Control Unit) added in this case is primarily responsible for controlling the added redundant systems and performing functions such as automatic/manual driving mode determination, fault diagnosis, and redundant system switching control. In this example, redundancy is achieved within the VCU-Additional to avoid it becoming a single point of failure.

Autonomous Driving System

In this configuration example, redundancy is achieved by using two ECUs, enabling fail-operational operation.