Sensing requirements for an automated vehicle for highway and rural environments

MSc thesis

K.J. Bussemaker

Technische Universiteit Delft

TU Delft Delft University of Technology

Challenge the future

SENSING REQUIREMENTS FOR AN AUTOMATED VEHICLE FOR HIGHWAY AND RURAL ENVIRONMENTS

MSC THESIS

by

K.J. Bussemaker

in partial fulfillment of the requirements for the degree of

Master of Science
in Mechanical Engineering

at the Delft University of Technology,
to be defended publicly on Thursday December 11, 2014 at 9:00 AM.

Supervisor:	Dr. ir. R. Happee
Thesis committee:	Ir. D. Kotiadis
	Prof. dr. ir. P. P. Jonker
	Dr. ir. T. Keviczky

An electronic version of this thesis is available at `http://repository.tudelft.nl/`.

Acknowledgement

I would like to thank my main supervisor, Riender Happee, for all the mentoring, expertise and constructive feedback I have recieved during this thesis project. Furthermore I want to thank my secondary supervisor, Dimitrios Kotiadis, for the feedback and especially for sharing his expertise on automotive sensors. I also would like to thank my other committee members, Pieter Jonker and Tamas Keviczky, for taking the time to review my work. And last but certainly not least, I want to thank my family and friends, both here and across the border, for all the support, laughter, good talks, coffee, and most of all for simply being there when I needed a little bit of distraction.

Abstract

Road statistics show that 95% of all car crashes are related to human error, and 30.000 people were killed on EU roads in 2011 alone. Automated driving has the potential of saving thousands of lives by removing human error from driving. In order to achieve automated driving, a vehicle needs an adequate set of sensors, which will basically be the eyes and ears of the vehicle. An automated vehicle has to detect other road users and should be able to interact with them in a safe way, hence it is important to understand what the vehicle's sensors should be capable of. We have listed the sensor metrics that are important to consider when selection a sensor set for an automated vehicle, and we have provided methods and equations on how to derive these metrics. Furthermore, we have listed the capabilities and drawbacks of different sensors, and have discussed possible solutions to enhance sensing performance and robustness. We have also looked at Advanced Driver Assistance Systems (ADAS) currently available on the market, in order to get a better perspective on the applications and capabilities of current state-of-the-art sensors.

In addition, we have investigated the different driving scenarios one can encounter in highway and rural driving environments, and sensing requirements have been derived for each of these scenarios based on the methods derived in this thesis. We have shown that automated highway driving should be possible, as longs as the effects of ego position error and heading measurement error are kept to a minimum. Automated driving in rural environments has turned out to be problematic, mainly due to reliability issues regarding pedestrian, cyclist and animal detection. Automation can be achieved for most of the rural scenarios discussed in this thesis (again assuming minimal ego position / heading measurement errors), however the human driver should always be ready to take back control due to these reliability issues.

The approach taken during this thesis is very theoretical, and further verification using simulations and road testing is recommended. However, the results found provide a good starting point for the selection of a sensor set for an automated vehicle, and can also be used to assess the capabilities of future technology.

Contents

Chapter 1

Introduction

Automated driving has been an active research area for the last couple of decades. Road statistics show that 95% of all car crashes are related to human error. In 2011, 30.000 people were killed on the roads in the European Union, and many more were injured [46]. Autonomous driving has the potential of saving thousands of lives by removing human error from driving. It can also help to make driving more efficient, which results in lower fuel costs and decreased impact on the environment.

The majority of car manufacturers are currently developing vehicles that can achieve different levels of automated driving. These levels which are defined as [46]:

Level 0. Driver only. Human driver executes manual driving task.

Level 1. Driver assistance. The driver permanently controls either longitudinal or lateral control. The other task can be automated to a certain extent by the assistance system.

Level 2. Partial Automation. The system takes over longitudinal and lateral control, the driver shall permanently monitor the system and shall be prepared to take over control at any time.

Level 3. High automation. The system takes over longitudinal and lateral control; the driver must no longer permanently monitor the system. In case of a take-over request, the driver must take-over control with a certain time buffer.

Level 4. Full automation. The system takes over longitudinal and lateral control completely and permanently. In case of a take-over request that is not carried out, the system will return to the minimal risk condition by itself.

The highest level of automation currently available on the market is Level 1, in the form of Advanced Driver Assistance Systems (ADAS), which support the driver by providing warning signals or by partially automating a specific driving task. More and more cars are being equipped with different kinds of ADAS systems. The ADAS systems themselves are constantly improving thanks to research and development by the automotive industry. Some examples of currently available ADAS systems are listed below, and a more extensive list is presented in chapter .

- Adaptive Cruise Control
- Lane Keeping Assist
- Advanced Emergency Braking
- Automatic Parking

Vehicles capable of achieving Partial, High and Full automation are currently being developed by several large automotive companies and research institutes. These research vehicles usually carry a large amount of sensors, and the amount and type(s) of sensors vary significantly between projects.

This thesis is part of the Dutch Automated Vehicle Initiative (DAVI project), an automated driving project involving the TU Delft and multiple industry and research partners. Knowledge from this study will be used to select and evaluate a sensor set for a (passenger) vehicle.

Problem formulation

An automated vehicle has to be aware of its surroundings to a certain degree in order to be able to drive safely. It has to detect vehicles, pedestrians, cyclists and in some cases (wild) animals in order to assess whether or not they pose a collision risk. In order to achieve proper detection, the vehicle has to be equipped with an adequate sensor set. But how can we define adequate?

First of all, driving in general can be separated into three different driving environments: highway, rural and urban, a division commonly seen in the literature. All these environments have different characteristics, i.e. pedestrians and cyclists can be encountered frequently in the urban environment, but much less frequently in rural environments, and are not allowed on a highway at all. Furthermore, different construction rules and guidelines apply to each environment. In this thesis, we have decided to focus on just the highway and rural environment. These environments have well-defined rules and guidelines which allows effective analysis of the different driving scenarios. Urban areas are very challenging with exotically shaped intersections and heavy pedestrian and cyclist clutter. In addition, a large autonomous urban driving competition already exists: the DARPA urban challenge (see section 2.6). This competition has already created a lot of interest in the field of autonomous urban driving, and many teams have published papers about their vehicles. In terms of sensing requirements, very little has been published for the highway and especially for the rural environment, hence we have decided to focus on these environments. Furthermore, this thesis focusses on the detection of other road users (vehicles, pedestrians, etc), however other sensing applications (for example lane marker detection) can be very useful for an automated vehicle, and some of these application will be discussed briefly in this thesis.

The research question of this thesis is: **What are the sensor specifications required to enable automated driving in Highway and Rural environments, and to what degree is current technology able to meet these requirements?** In order to answer this question, the following aspects had to be addressed:

- Investigate existing literature, which was mostly done by investigation existing research vehicle projects. It turns out that only limited information is available. Research is carried out mainly by large automotive companies, and since the automotive sector is a highly competitive market, much of the information is kept in-house.
- Identifying different types of sensors available for automotive use. Important sensing metrics have been listed, and have been discussed for all sensor types. A common-off-the-shelve (COTS) comparison has been carried out for each sensor, in order to get a good overview of the specifications of the available products.
- Investigate ADAS systems currently on the market. For each system, the typical sensor set was identified in order to get a better idea of how certain sensors can be applied.
- Create a comprehensive list of driving scenarios. As mention before, driving in general can be seperated in three driving environments: Highway, Rural and Urban, and we have decided to focus on highway and rural only. Common scenarios have been listed for each of these driving environments, based on literature. Special maneuvers, such as U-turns, parking, roadworks etcetera have been left out in order to focus on the main aspects of (automated) driving.
- Identifying and discussing problems that can occur when selecting a sensor set, and how to overcome these.

The first three items have been investigated as part of a literature study prior to this thesis. The majority of this literature study is incorporated in this thesis report in order to provide a complete picture and to ensure that all information is in one place. In this thesis, we will mainly focus on the identification and analysis of the different scenarios that can be encounted during when driving on highway and through rural areas. We will also discuss what can and can't be achieved using the current state-of-the-art technology available on the market. This information can be used to select and verify a sensor set required to cover a specific set of driving scenarios.

Chapter 2

Automated research vehicles

In this chapter, we will investigate some of the major research projects in the field of automated driving, with a strong focus on sensing. Most of the research in the field of automated driving is carried out by (automotive) companies, hence there is not much public information available. However, the vehicles discussed in this chapter provide examples of how different sensing needs are being addressed, in a global sense.

2.1 Google driverless car

Figure 2.1: One of Google's automated Toyota Priuses (source: IEEE)

Google's automated Toyota Prius vehicles [39] have traveled more than 300.000 km on public roads. The vehicle's main sensor is a large Velodyne HDL 64E LIDAR unit mounted on the roof, which creates a high-resolution map of the surroundings, 360 degrees around the vehicle. In addition, 4 RADAR units are used (3 on the front bumper, 1 on the rear bumper), with sufficiently large range for the detection of vehicles on highways. A camera sensor mounted behind the rearview mirror, which is used to detect traffic lights. Furthermore, a GPS / INS and wheel encoder are used to accurately determine the vehicle position. In order to be able to autonomously drive in a certain area, the vehicle must be driven through it manually first, so it can create a map of the environment. When the vehicle drives autonomously, it compares fresh data with the environment map, which allows it do differentiate with pedestrians and stationary objects.

2.2 BMW connected drive

Figure 2.2: BMW's connected drive test vehicle (source: BMW)

BMW's connect drive project [12] focusses mainly on automating highway functions. Their test vehicles are equipped with RADAR, LIDAR, ultrasonic and vision systems. BMW is collaborating with automotive sensor supplier Continental.

2.3 Mercedes S 500 Intelligent Drive

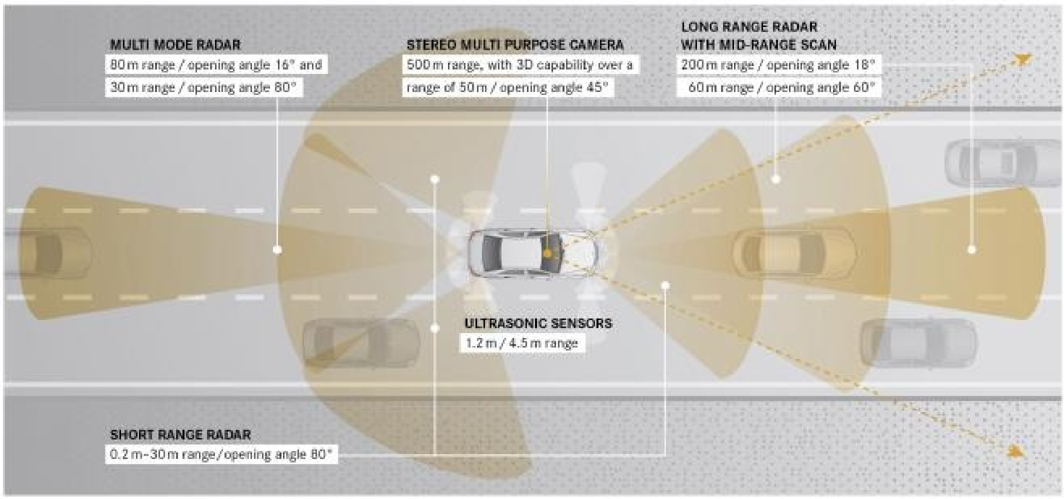


Figure 2.3: Sensor layout of the new Mercedes S class (source: media.daimler.com [21])

Mercedes is using its new S class vehicle as the basis for their automated driving research. The S class is already equipped with 6 RADAR sensors, a stereo camera, and several ultrasonic sensors [21], as shown in figure 2.3.

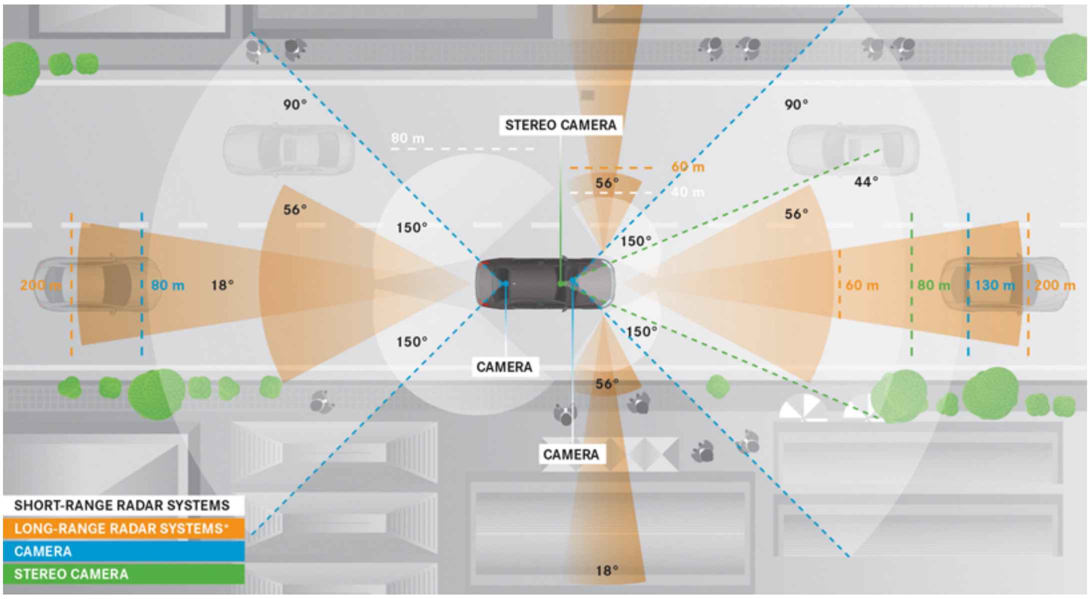


Figure 2.4: Sensor layout of the Intelligent Drive vehicle (source: media.daimler.com). Overlap of sensors is much greater in reality [57].

In addition to the sensor set of the regular S class, the Intelligent Drive vehicle has extra RADAR and camera sensors [57] (see figure 2.4). Two long-range dual beam Continental RADARs are used for lateral detection, while four short-range RADARs (custom units developed by Delphi) were installed to improve sensing of the immediate surroundings and other road users [24]. An extra forward-looking camera installed behind the windscreen is used for traffic light detection. A backward-looking camera is used to determine the exact position of the vehicle (by detecting known features), assisting the GPS system.

2.4 Toyota / Lexus Research Vehicle

Figure 2.5: Toyota/Lexus Research Vehicle (source: arstechnica.net

Toyota vehicle carries a 360 degree FOV LIDAR mounted on the roof (range 70 m), 3 color cameras (1 facing forward, 2 facing sideways, range 150 m) for vehicle and traffic light detection, front and side-facing RADARs for the detection and speed determination of vehicles, and finally a GPS / INS system to determine the position [80].

2.5 VisLab BRAiVE

Figure 2.6: VisLab's BRAiVE vehicle

The BRAiVE vehicle [37] is a fully autonomous vehicle developed by VisLab, a company lead by Alberto Broggi, a leading researcher in the field of automated driving. VisLab has 15 years of experience in the field of automated driving, and mainly focusses on (3D) vision as the sensing input for their vehicles. The BRAiVE vehicle features 10 cameras, 5 LIDARs and a GPS/INS unit. Their placement and application are explained in figure 2.7 and 2.8.

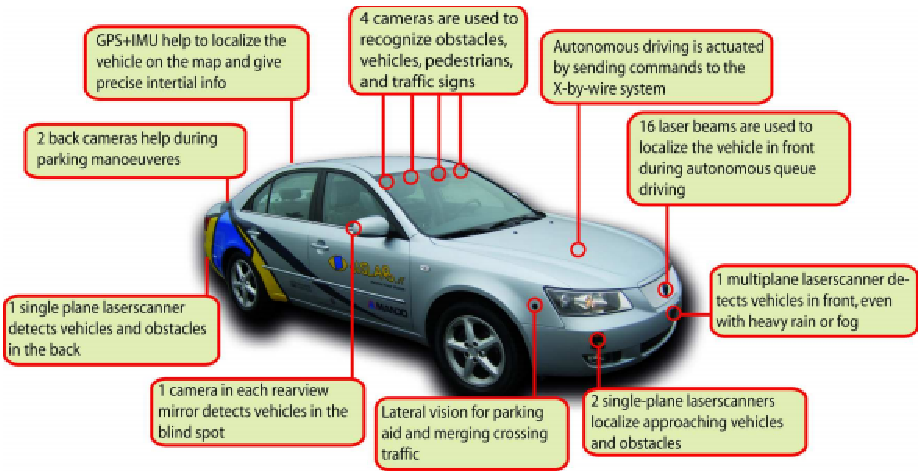


Figure 2.7: Placement and application of sensors on BRAiVE vehicle (source: [37])

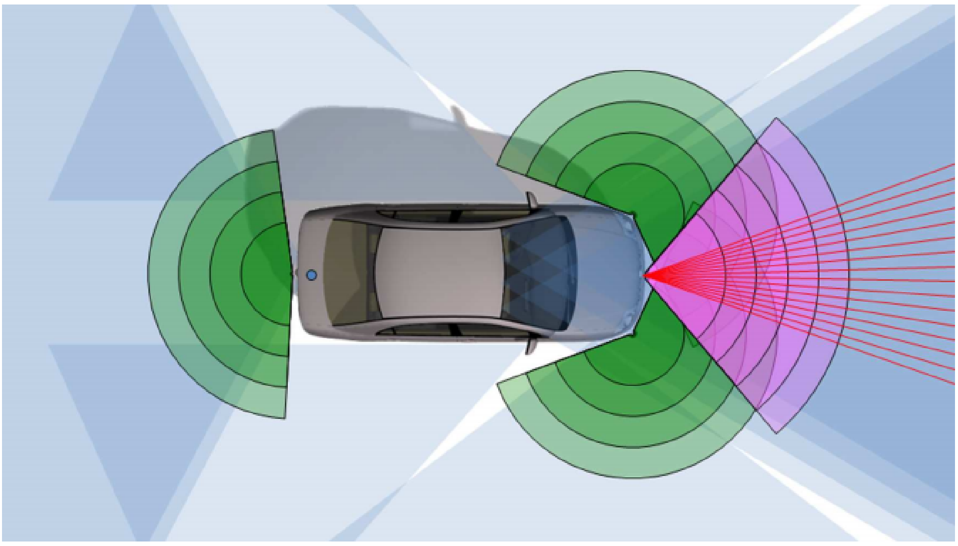


Figure 2.8: Detection coverage of sensors on BRAiVE vehicle (source: [37])

2.6 DARPA Urban Challenge

Figure 2.9: The 'Boss' Vehicle (source: low-powerdesign.com) won the 2007 DARPA urban challenge

In the DARPA Urban Challenge, fully automated vehicles have to maneuver their way through an urban environment. These vehicles have to perform regular driving tasks such as turning and keeping headway, as well as special maneuvers such as parking, U-turns, etc. Many teams from universities all over the world compete in this challenge. Although many teams have published papers about their vehicles, the challenge organization enforces pre-defined rules and time gaps for many of the maneuvers [22], which do not necessarily match the real world scenarios that an automated vehicle might encounter. Another problem is the abundance of sensors typically used by the teams. Figure 2.9 shows the Boss vehicle. It uses 11 (!) LIDAR sensors (4 different types), 5 long-range dynamic RADARs (Continental ARS300), and two cameras. These teams focus on research and the challenge, not on the developing a product that could eventually become ready for the market. This makes it difficult to apply their findings on a vehicle that has to be market-feasible.

Chapter 3

ADAS systems

In this chapter, we will investigate Advanced Driver Assistance Systems (ADAS) currently available on the market. By investigating ADAS systems, we can get a global idea of which sensors are used by which type of systems. It will give us a better understanding of capabilities and limitations of the different types of sensors.

3.1 Adaptive Cruise Control (ACC)

Adaptive Cruise Control systems can take control of the engine and brake in order to make the vehicle travel at a specific speed. If this is not possible due to a slower-moving lead vehicle, the ACC system will maintain a safe headway distance to this lead vehicle. Early ACC systems were only able to operate above a specific speed limit (typically 30-40 km/h), due to sensor limitations [71]. However, ACC with stop and go functionality has been developed, which allows operation at low speeds, all the way down to full standstill. These modern ACC systems commonly use RADAR (sometimes LIDAR [79]) together with vision systems to detect objects, typically having a range of 150-200 meters and can operate at speeds of 0-200 km/h [56, 11].

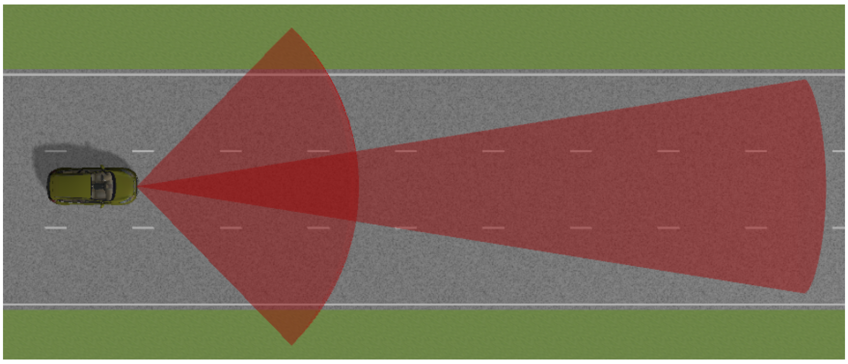


Figure 3.1: Typical detection coverage of an ACC system

3.2 Advanced Emergency Braking System (AEBS)

AEBS systems are forward-looking assistance systems that can help the driver to avoid a rear-end collision with a vehicle ahead of the host vehicle. These systems commonly use ACC sensor technology [38]. These systems can be split into three categories:

- Forward Collision Warning systems (FCW) check the traffic ahead for impending collisions. and issue a warning signal if the driver does not respond to this collision threat. FCW systems typically operate at speeds of 10-180 km/h [38].
- Collision Mitigation Braking Systems (CMBS) are essentially FCW systems, but will automatically apply full brakes if a collision is unavoidable, trying to mitigate the effects of the crash. Like FCW systems, they can operate at speeds of 10-180 km/h [38].

- Unlike a CMBS and FCW system, a Collision Avoidance system [38] will attempt to completely avoid a crash by applying the brakes before a collision becomes unavoidable. Current systems are able to fully avoid a collision up to 40 km/h [3]. At higher speeds, the systems will mitigate the effects of the collision.

3.3 Lane Departure Warning (LDW)

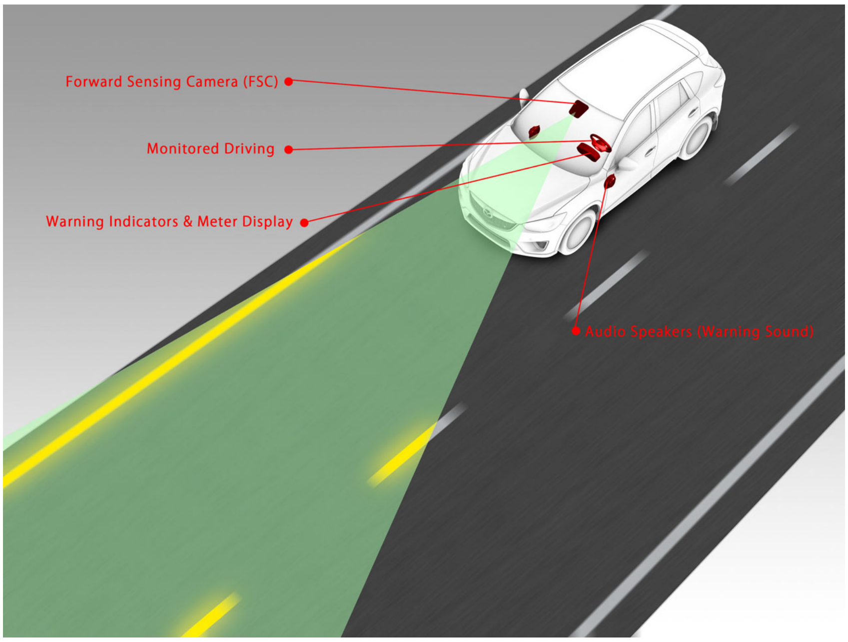


Figure 3.2: Vision based LDW (source: Mazda)

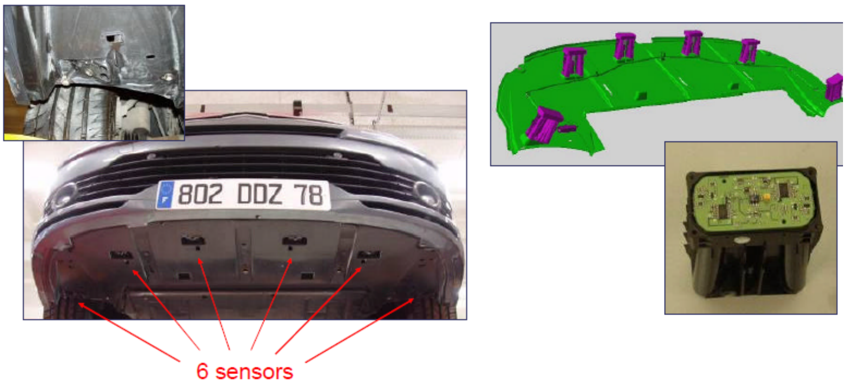


Figure 3.3: Infrared sensor based LDW (source: PSA Peugeot CitroÃńn)

A Lane Depature Warning system [69, 82] warns the driver if he or she is about to unintentionally leave the current lane. The system tracks the lane markings using a forward-looking vision system to determine the position within the current lane. A system using infrared sensors also exists [69], these sensors are mounted underneath the front bumper and are looking straight down onto the road surface. An LDW system only provides warnings and does not act. LDW systems can typically operate at curves with a radius of 230 m or higher [82].

3.4 Lane Keeping Assist (LKA)

A Lane Keeping Assist System is an extended version of an LDW system. In addition to issueing warnings, LDW systems can also actively correct the driver. Corrective steering or braking is applied to prevent an unintended lane departure. LKA systems use forward looking camera sensors. The currently existing LKA systems are designed for motorway use [84], therefore these systems will only work above speeds of around 65 km/h and on curves with a radius larger than 230 m [82].

3.5 Lane Change Assist (LCA)

Lane Change Assist systems assist the driver during the execution of a lane-change maneuver. The system scans the adjacent lanes for vehicles, and will alert the driver if a hazardous situation occurs. These systems can be split into two categories:

- Blind Spot Monitoring (BSM) systems check the blind spots for any presence of vehicles, and generate warning signals in case of a collision hazard. These systems typically use cameras or RADAR sensors, and cover and area of 3.5 m laterally from the vehicle, and 9.5 m behind the vehicle's side-view mirrors [8], as shown in figure 3.4. BSM systems operate at speeds above 10 - 30 km/h depending on the make and model [82].

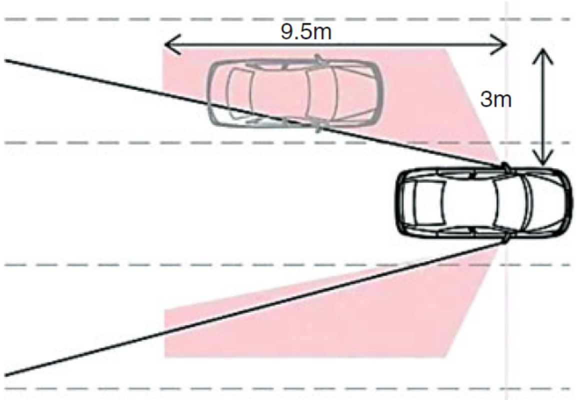


Figure 3.4: Typical detection area of a BSM system (Source: Gizmag)

- Lane Change Warning (LCW) systems are similar to BSM systems, but are also able to detect traffic approaching from behind, by covering the adjacent lanes up to 90 meters behind the host vehicle [82, 5], as shown in figure 3.5. Like BSM systems, LCW uses RADAR for detection, and will issue warnings when a hazardous situation is detected. LCW systems typically work above speeds of 30 km/h [8].

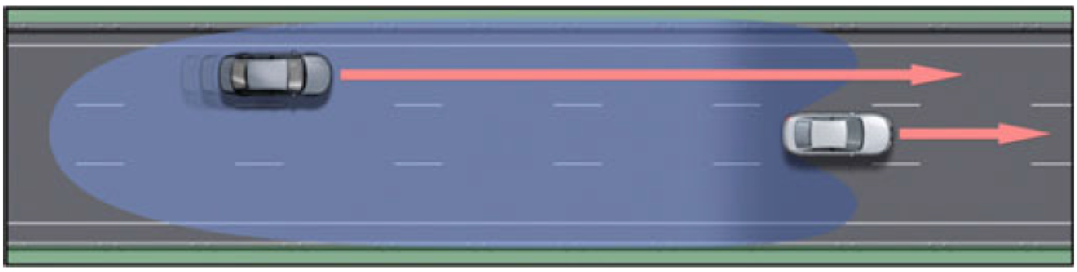


Figure 3.5: Typical detection area of an LCW system (Source: Audi)

3.6 Night Vision

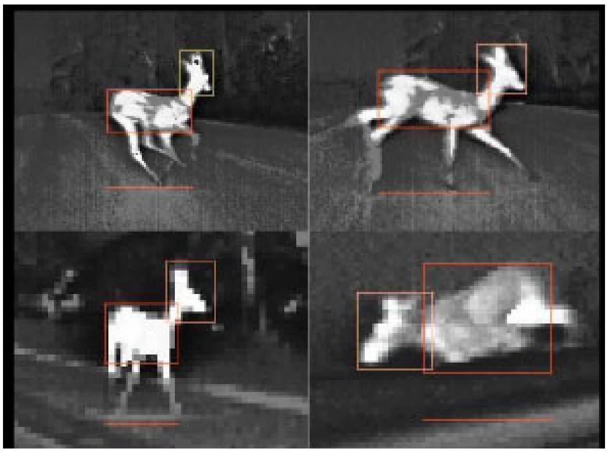


Figure 3.6: Animal detected using a FIR night vision camera (source: Autoliv)

Night vision sensors use the infrared spectrum to detect objects at night. Currently available night vision systems use a screen to display their detected image. Image recognition algorithms can detect pedestrians and animals [6][52], and warnings are issued to the driver. The driver use the screen to directly extend his range of vision far beyond the reach of low-beam headlights, which is approximately 40 meters at night.

Two types of night vision sensors can be distinguished: Near-infrared (NIR) and Far-infrared (FIR). NIR systems require an active IR source, which is usually mounted in the headlights. This unfortunately means that NIR systems can be blinded by NIR systems carried by any opposing traffic. Xenon headlight bulbs also emit a wide spectrum of light, which could blind a NIR sensor. FIR systems are passive, and take advantage of the natural thermal radiation emitted by all objects hotter than 0 ° K. FIR systems use differences in temperature to distinguish objects, therefore these systems are typically used to detect cyclists, pedestrians and animals. If the temperature difference w.r.t. the environment is small, a FIR system might not be able to detect the object [35].

3.7 Traffic Sign Recognition (TSR)

Figure 3.7: A detected road sign (Source: Nvidia)

Traffic sign recognition systems enable the detection and classification of traffic signs. Image processing algorithms process the information provided by a camera system, and show the information to the driver. The detection range and accuracy of the system depend on the camera properties and the image processing algorithm used.

3.8 Pedestrian Detection

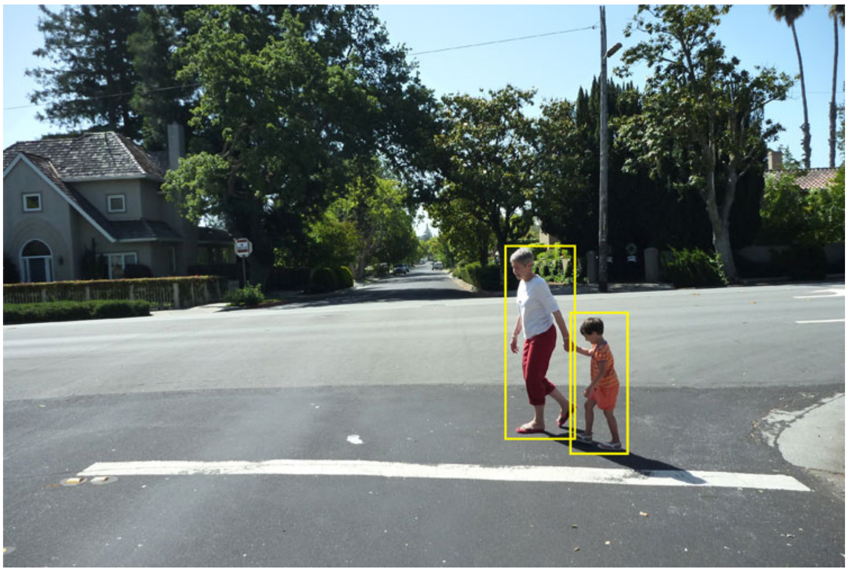


Figure 3.8: Two detected pedestrians (Source: Nvidia)

Pedestrian detection systems are able to detect pedestrians and assess their risk. These systems can be an integrated part of i.e. an AEBS system, and apply full braking in order to prevent or mitigate a collision with a pedestrian. These systems commonly use RADAR fused with a vision system, where the RADAR system is used to detect objects, and the vision system is mainly used to classify the object and check whether or not it is a pedestrian [16]. Research has shown that LIDAR based systems can also work [26, 67] , but these are not available on the market. Night vision systems can also be used to detect pedestrians in low lighting conditions (see section 3.6 about Night Vision).

3.9 Automatic Parking

The first parking assist systems were developed to assist the driver during the parallel parking task. These systems typically use ultrasonic sensors to measure the distance to other vehicles or objects, and will issue a beeping warning sound, where the frequency of the beeps resembles the measured distance. These ultrasonic systems are used both at the front and the back of the vehicle. Some systems also feature a backward-facing camera system mounted at the rear-end of the vehicle, which helps the driver to visually check the space behind the vehicle.

Automatic parking systems were later developed to enable a vehicle to park itself with little or no driver interference. These systems are typically able to assist in parallel parking, although Volkswagen's new system also has the ability to perform a perpendicular parking maneuver [83]. These systems typically use side-mounted ultrasonic sensors to determine the size of a parking slot as the vehicle drives by, and signals the driver that the slot is large enough and that the maneuver can be initiated. The driver usually has to control the gas and brake pedal, while the system controls the steering wheel. Forward and backward-facing ultrasonic sensors check the distance to any vehicles or objects, and warn the driver in a way similar to the more simple parking assist systems.

3.10 Digital Maps

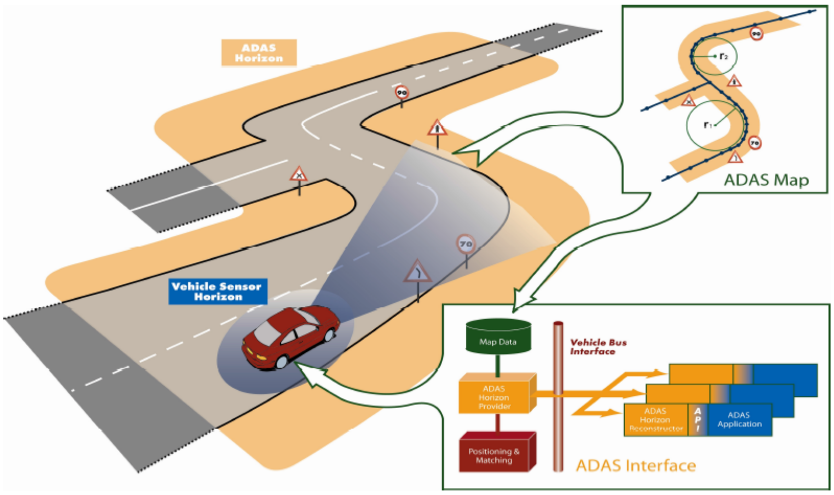


Figure 3.9: Working principle of a digital maps system (Source: Ertico / ADASIS)

Digital maps have been available in the form of navigation systems, but these provide high-level map data, which is not always sufficient for ADAS or automated driving purposes. Recent developments are focusing on the integration of ADAS systems with map data. BMW has already produced an ACC system which used navigation map data for functional enhancements in 2004 [48]. Automotive companies are currently cooperating to develop a mapping standard [49], and Continental currently offers a system called eHorizon [19].

Chapter 4

Sensors and metrics

In this chapter we will thoroughly investigate the different sensors that are available for automotive use. We will discuss sensor metrics that are important to concider when picking a sensor set, and how they relate to some of the important aspects of automated driving, along with the calculations that we will later use to determine the requirements for such a sensor set. We will also investigate the different types of sensors available for automotive use, and identify specific characteristics and possible problems. We will also provide a common off-the-shelve (COTS) comparison if possible, which should give us a better indication of what the state-of-the-art technology is capable of. Finally, we will briefly discuss the concept of sensor fusion and how it can help achieving better sensing performance.

It should be noted that we have approached autonomous driving as a 2D problem. This means we simply ignore effects of elevation differences, and approach the problem from a helicopter perspective. In real life elevation differences do occur, but design limits are put up mainly to prevent issues with sight distance [25] [7]. Furthermore, we have decided to leave out Time-of-flight sensors in our discussion about sensing metrics in section 4.1. ToF sensors are a relatively new type of sensor that's not available for automotive use (yet), however this type of sensor is still mentioned in section 4.2 for completeness.

4.1 Sensor metrics

The sensor metrics will ultimately determine the performance of the sensor in a specific application, and therefore it is important to know what these metrics mean. The following metrics are the most important when selecting a sensor for automotive purposes:

- **Range**. This determines what the sensor can cover in terms of distance.
- **Field-of-view (FOV)**. This is the opening angle of the sensor, and together with the range it provides a pie-slice shaped coverage pattern. An example is shown in figure 4.1.
- **Resolution**:
  - **Range**. The meaning of resolution is different for each sensor, and will be discussed later.
  - **Angular**. „
- **Accuracy**:
  - **Range**. How much the measured distance actually deviates from the real distance. The accuracy of a sensor dictates how much the measured value can deviate with respect to the actual value. For example, for a sensor with a range accuracy of 1 m, a measured distance of 11 meters can be expected to be between 10 and 12 meters in reality.
  - **Angular**. How much the measured angle actually deviates from the real angle.

It should be noted that resolution and accuracy are two very distinct properties that should not be confused with eachother. The accuracy of a sensor does not depend on the sensor's resolution [88] [20] [70].

The metrics mentioned in this section don't mean much on their own. In the next sections we will illustrate what the implications of the sensor metrics are for some essential processes required for autonomous driving.

4.1.1 FOV & range: detection coverage

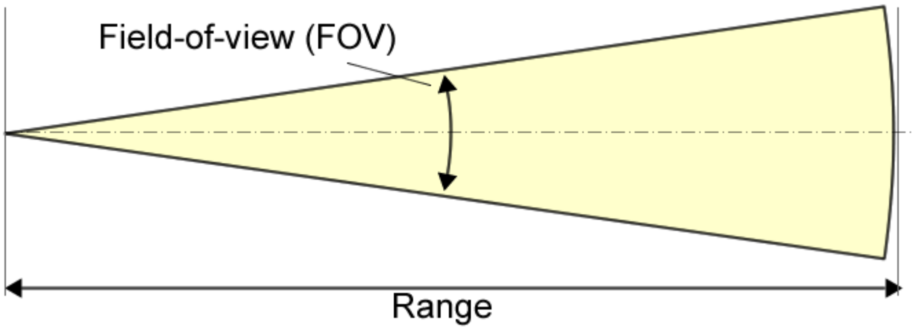


Figure 4.1: The range and FOV of a sensor determine the detection coverage

The range and FOV together determine what the sensor is actually able to cover and therefore 'see'. It should be noted that in the FOV is composed out of a horizontal (azimuth) and vertical component (elevation). Figure 4.1 only shows a 2D illustration. As discussed earlier, we are approaching driving as a two-dimensional problem, hence the term FOV refers to the horizontal FOV. The vertical FOV is less relevant and is mainly important when dealing with differences in elevation, which we are not considering. It should also be noted that the effective range of a sensor depends on the size of an object: larger objects are easier to detect.

Range

So what determines the required detection coverage? First of all, we need to determine at what distance the host vehicle has to detect other traffic. In some cases, i.e. a emergency stop scenario, it makes sense to calculate the required stopping distance. If we assume a constant acceleration a, and a duration t of a stopping maneuver from initial speed v_0 to end speed v_1 can be calculated using:

$$t = \frac{v_1 - v_0}{a} \tag{4.1}$$

The stopping distance can then be calculated using:

$$d_{stop} = v_0 t + 0.5at^2 \tag{4.2}$$

In some cases a reaction time t_{react} has to be included in the calculations. An example of such a case is the 'lane sharing' scenario discussed in section 6.1.5. In this scenario, the host vehicle is sharing a lane with a vehicle driving in the opposite direction. Since it is highly likely that this vehicle is operated by a human driver (at the time of writing at least), we have to take his or her reaction time into account. This leads to the following equation:

$$d_{stop} = v_0(t + t_{react}) + 0.5at^2 \tag{4.3}$$

In other cases, the required range can be calculated using a measure called time-to-collision, commonly abbreviated as TTC. TTC describes the time it will take for two vehicles to collide, assuming both vehicles keep driving at a constant velocity. If we concider a distance d_{AB} between vehicles A and B, TTC (τ) is calculated using:

$$\tau = \frac{d_{AB}}{v_A - v_B} \tag{4.4}$$

Lots of research about drivers accepting specific TTC values (commonly refered to as 'gap acceptance') has been carried out, i.e. for lane change maneuvers on the highway, or for laterally approaching traffic at an intersection. Equation 4.4 allows us to calculate the required sensing range for such cases. By assuming both vehicles drive at a constant velocity, one is able to calculate the required sensing range r using equation 4.5.

$$r = d_{AB} = \tau(v_A - v_B) \tag{4.5}$$

FOV

The other part that determines the required sensor coverage is the FOV. The nice thing about the FOV of a sensor is that if one single sensor is not sufficient to meet the requirements, one can simply add more sensors to increase the coverage. In addition, sensors can be configured in a way that their FOVs overlap, which adds robustness. We will not set hard limits for the required FOV. Instead, we will provide an image of the required detection coverage for each scenario in our highway and rural environment analysis chapters. This allows us to provide a more general and unbiased picture of what's actually required.

4.1.2 Angular resolution

Figure 4.2: A situation where object seperation is essential (source: google streetview)

In order to properly assess detected vehicles and what threat they pose to the host vehicle, the sensors should be able to separate objects properly. The sensor's angular resolution plays a key role in this process. A low angular resolution could mean that two vehicles driving next to eachother could be perceived as one single vehicle, which in turn could lead to wrong risk estimates and ultimately wrong decisionmaking. An example is shown in figure 4.2. The grey and red vehicle are at approximately the same distance, which could lead them being detected as one vehicle if the sensor's resolution is not adequate.

RADAR

A RADAR's detection beam can be separated into resolution cells (for a thorough explaination, see section 4.2.3). If two objects are within the same resolution cell, the RADAR is unable to distinguish these objects, hence they will be perceived as one large object, unless their speed difference is sufficiently large to allow separation based on velocity information [50] [89] [20]. Assuming small angles, the relation between α (angular resolution, in radians) and the distance d between two point at range R can be decribed using [20]:

$$d = \alpha \cdot R \tag{4.6}$$

Using this formula, the required angular resolution α can be calculated, which depends on the minimal required value of d. This value will be derived later during our in-depth scenario analysis later in this thesis.

LIDAR

A LIDAR returns a point cloud, which has to be processed in order to detect and track objects. From [81] we can conclude that the separation between two objects can be guaranteed if the LIDAR gets no (or a significantly different) return between the two objects. Lets assume we have a LIDAR with angular resolution α. The distance required to quarantee one miss at distance r can again be calculated using equation 4.6.

Vision

Although vision systems typically have a large angular resolution (due to their large number of horizontal pixels), their object discrimination performance heavily depends on the image processing algorithms and the size of a vehicle's representation in pixels on the imager. Therefore we can't provide a formula that allows us to calculate the required angular resolution.

4.1.3 Range resolution

RADAR

The range resolution of a sensor represents the smallest difference in distance that can be measured, and like the angular resolution, it determines weather or not two objects can be separated or if they are perceived as one [20]. Figure 4.3 illustrates how an enhanced range resolution can enable the ability to seperate two objects. In the left half of the figure, both gray vehicles fall within one resolution cell and will therefore be perceived as one object. In the right half of the figure however, both vehicles fall in their own separate resolution cell, which allows them to be perceived as two individual objects. For a detailed about resolution cells, see section 4.2.3.

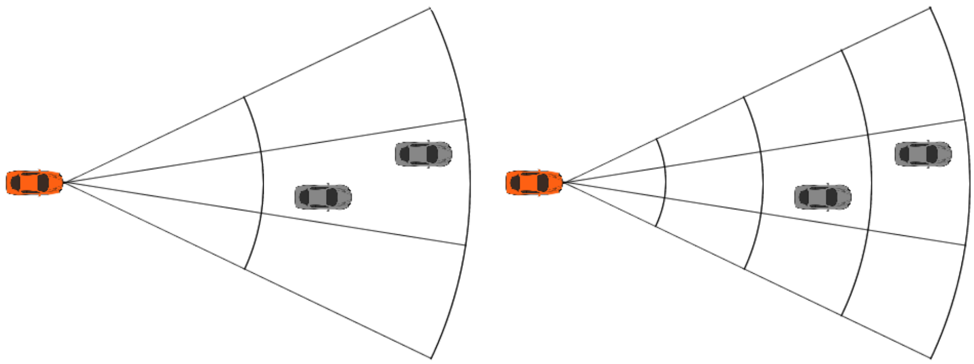


Figure 4.3: Resolution cells with coarse (L) and fine (R) range resolution values

LIDAR

Like RADAR sensors, LIDARs can experience problems separating between two signals. Several pulses can be in the air due to the typically high firing rate, and a single pulse can reflect off multiple objects. As a result, the principe explained for RADARs also applies to LIDAR sensors, hence a LIDAR is not necessarily able to separate between objects that are to close to eachother in terms of distance [70]. However, the range resolution of LIDARs is typically a lot better compared to RADAR sensors.

Vision

Stereo vision calculates its depth based on disparity between two distinct images, there it is not possible to define a range resolution for vision systems.

Remarks

Although a high range resolution is beneficial as it further enhances the ability to seperate between targets (see figure 4.3), it is not as critical as the angular resolution. There's always a likely possibility that two vehicles are travelling parallel at an equal distance, which could lead to the vehicles being perceived as one regardless of the range resolution (see section 4.1.2 for a detailed explanation on angular resolution). Imagine a highway scenario where one vehicle is passing another vehicle (see figure 4.2): at some point the two vehicles will be driving next to eachother at the same distance w.r.t. the sensor, and whether or not the sensor is able to distinguish between the two vehicles at that moment will depend on the angular resolution. We will not concider it in our further analysis because of the reasons mentioned above.

4.1.4 Accuracy

An automated vehicle should be able to detect vehicles and other objects with a certain degree of accuracy. This accuracy is important for estimating the threat level of detected vehicles and other objects. A key example is lane localization, which is the task of estimating in which lane a vehicle is driving. In this section we will use the lane localization example to determine criteria for the required sensor accuracy. Unfortunately, limited information related to lane localization and the required accuracy was found in the literature. We will therefore have to take a quite simplistic approach to determining in which lane a vehicle is. In [74], a camera system is used to detect both lane boundaries and vehicles, and a vehicle is associated to a specific lane if the vehicle center falls within the lane boundaries. We will assume usage of the same method and will base our accuracy requirements on that.

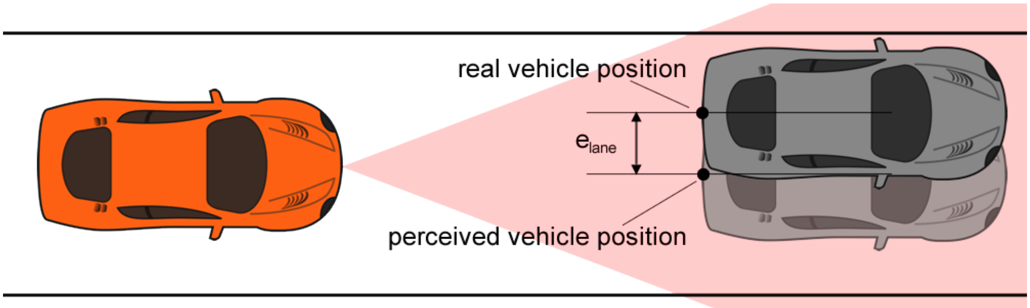


Figure 4.4: Lane localization error

In order to achieve proper lane localization, we have to measure the position of any detected vehicle, and have to compare it to the lane boundary information in order to determine on which lane it is. This might sounds like a simple task, but we have to concider several different errors that can disrupt this process:

- Ego position error. The host vehicle needs to needs to know where it is w.r.t the environment in order to assess correctly where the lane boundaries are.
- Heading error. This error is angular, which means it is proportional to the distance between the host vehicle and the detected vehicle.
- Angle measurement error. Any error in the angle reported by the sensor causes an error proportional to the distance between both vehicles. Again, the effects of this error are proportional to the detection distance.
- Distance measurement error. Distance measurement error can be a significant factor on i.e. roads that are peperpendicular to the host vehicle, such as rural intersections.
- Lane boundary position error. In order to assess if a vehicle is between the lane boundaries, the vehicle has to know where these boundaries actually are. Detecting lane boundaries is usually achieved using map data, through (optical) lane detection, or both. In all cases, any error in the position of the lane add ups to the total error.
- Interpretation error of the sensor's internal algorithms. For example one may expect a sensor or algorithm to report the center of a detected vehicle, but this center might deviate from the actual vehicle center.

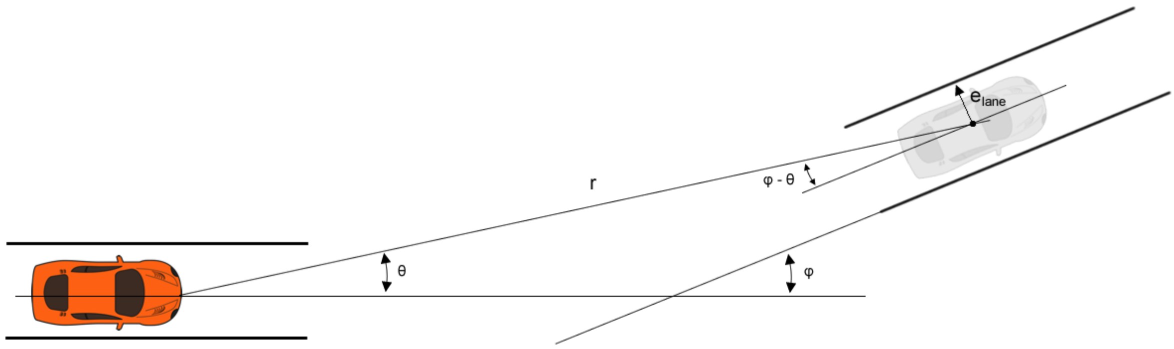


Figure 4.5: Coordinate system used to describe measurement error effects

For simplicity sake, lets assume that the sensor always reports the same point on a detected vehicle, i.e. the vehicle center. This allows us to neglect the interpretation error. Please take a good look at figure 4.5, which illustrates the coordinate system we will use for further calculations. In addition, we will define the following variables for the errors described earlier:

- E_{lat} - lateral ego position error
- E_{long} - longitudinal ego position error
- E_{head} - ego heading error
- E_{θ} - angle measurement error
- E_{range} - range measurement error
- E_{envir} - error due to inaccurate knowledge about the environment (i.e. digital map inaccuracy)

Lets assume that E_{envir} is direction independent. Through trigoniometric reasoning (see figure 4.5), we can describe the total lateral position error relative to the lane boundary as:

$$e_{lane} = \cos(\theta - \varphi) \cdot (E_{lat} + r \cdot (E_{head} + E_{\theta})) + \sin(\theta - \varphi) \cdot (E_{long} + E_{range}) + E_{envir} \tag{4.7}$$

Equation 4.7 is quite complex, and in order to be able to define limits on sensor accuracy we need to simplify things. We will make the following assumptions:

- Perfect knowledge about road geometry (i.e. perfect map data or perfect lane boundary detection). $E_{envir} = 0$.
- Perfect ego position measurement. $E_{lat} = 0$ and $E_{long} = 0$.
- Perfect ego heading measurement. $E_{head} = 0$.

These assumptions allow us to reduce equation 4.7 to:

$$e_{lane} = \cos(\theta - \varphi) \cdot r \cdot E_{\theta} + \sin(\theta - \varphi) \cdot E_{range} \tag{4.8}$$

Equation 4.8 only includes the range and angular measurement errors. Furthermore, due the sin and cos terms, the effect of E_{range} decreases when the effect E_{θ} increases, and vice versa. This is interesting because it allows us to neglect these factors in some cases. We will now illustrate this with some examples.

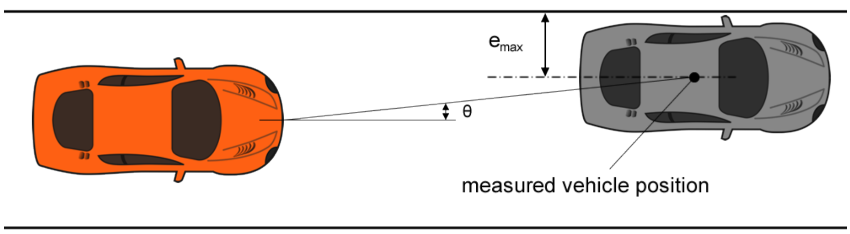


Figure 4.6: Car following within a single straight lane

Figure 4.6 shows the same scenario presented earlier, where two vehicles are driving in the same lane. Since both vehicles are driving in the same lane, θ will be small. Hence equation 4.8 can be reduced to:

$$e_{lane} = r \cdot E_{\theta} \cdot \cos(\theta - \varphi) \tag{4.9}$$

In the case of two vehicles driving on the same lane, then $\cos\theta \approx 1$. But what if the lead vehicle is driving in one of the adjacent lanes instead? At long distances, θ will still be small, however at shorter distances (see figure 4.7) θ will increase, which means that the $\sin(\theta - \varphi)$ term in equation 4.8 can no longer be neglected, hence the effects of E_{range} increase. At the same time, $\cos\theta$ will become smaller, as well as the range r, making E_{θ} less influential. For $|\theta|$ close to 90°, equation 4.8 reduces to:

$$e_{lane} = E_{range} \cdot \sin(\theta - \varphi) \tag{4.10}$$

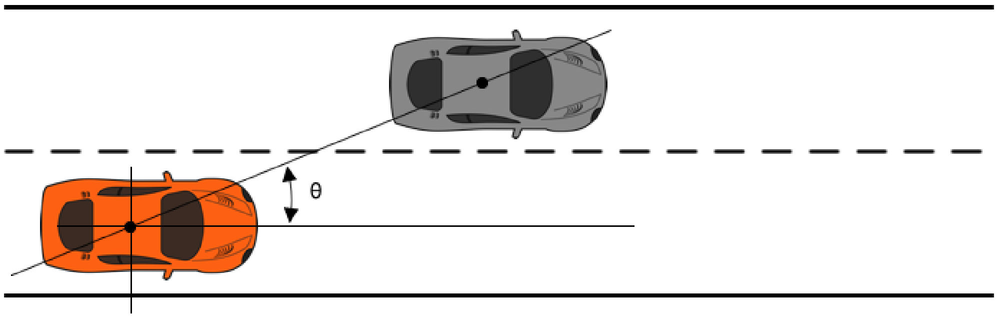


Figure 4.7: Large θ in case of a nearby vehicle in the adjacent lane

So what this all mean for the accuracy requirements for this case? Since the vehicles are driving on the same road, we can assume that φ is close to 0, which means we can simply neglect it. Since $|\cos| \leq 1$ for any angle, we can define the limit for the angular error as:

$$E_{\theta} \cdot r < e_{max} \tag{4.11}$$

Since $|\sin| \leq 1$, we can define the limit for the range error as:

$$E_{range} < e_{max} \tag{4.12}$$

It should be noted that even though this example is about two vehicles driving on a straight, the equations derived in this section are not just limited to such a situation. An different example situation is shown in figure 4.8. The vehicle approaching from the left is quite far away, therefore $\theta \approx 90°$. In addition, the roads of the intersection also form a 90° angle, which results in $\theta - \varphi$ still being close to 0, just like the case described earlier (and illustrated in figure 4.6).

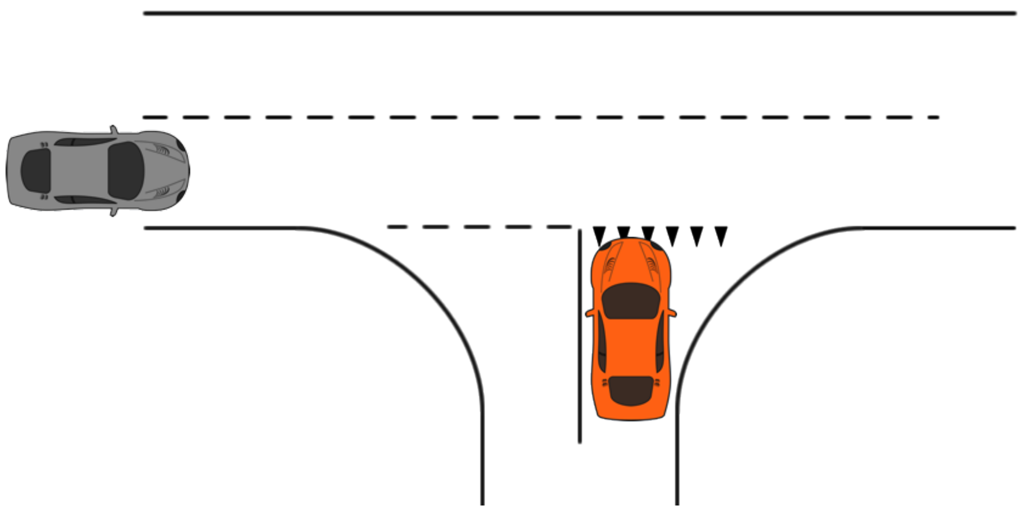


Figure 4.8: An intersection with a vehicle approaching laterally

It should also be noted that the $\theta - \varphi$ increases as the gray vehicle comes closer to the host vehicle. This is exactly the same problem as was illustrated in figure 4.7. The solution is again to limit the range error using equation 4.12, which guarantees adequate accuracy to facilitate lane localization.

Defining e_{max}

We have derived the calculations that describe how measurement errors translate into a lane positioning error. We now have to define how large this error can become before problems arise. As mentioned earlier in this section, [74] associates a detected vehicle with a specific lane if the vehicle center falls within the detected lane boundaries. Lets assume that none of the vehicles will ever cross its lane boundaries unless it deliberately wants to (i.e. during a lane change maneuver), in other words it stays in its current lane. This would mean that the detected center position (indicated by the blue dots in figure 4.9) will always stay within the blue shaded area in figure 4.9. The areas between the blue area and the lane boundaries, on both sides of the vehicle, are exactly half a vehicle width wide. We will call this width e_{max}. The system should be able to perform a correct lane localization as long as the measured vehicle position falls within the lane boundaries. This should be the case as long as the measured vehicle position does not deviate more than e_{max} in lateral direction. It should be noted that e_{max} depends on the width of the detected vehicle (or other object), and is independent of the lane width. It should also be noted that this is a somewhat simplistic approach, mainly due to the lack of available literature on this subject.

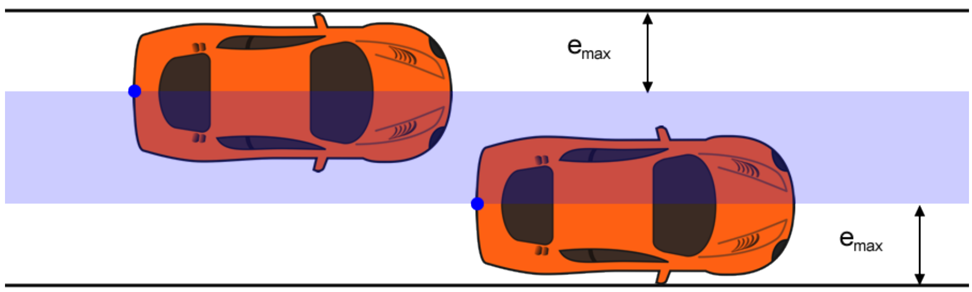


Figure 4.9: Maximum lateral error allowed in lane determination

In [2] a minimum vehicle width of 1.4 m is defined, which would mean $e_{max} = 0.7$ m. We can apply the same trick for motorcyclists, pedestrians and cyclists. These road users are more narrow and require a more accurate measurement if we again assume that they will stay within their lane boundaries. According to [58], the average width of a motorcycle is 0.64 m, while the average width of a cyclist is 0.45 m, which we be the values used by us. Furthermore we will assume that any pedestrian is at least 25 cm wide when seen from the side, based on anthropometric data from [1]. The values are summarized in table 4.1.

Road user	Minimum width [m]	e_{max} [m]
Vehicle	1.4	0.7
Motorcycle	0.64	0.32
Bicycle	0.45	0.225
Pedestrian	0.25	0.125

Table 4.1: Maximum error values for different types of road users

4.2 Sensor types

In this section we will discuss the various sensors available for automotive use. It should be noted that we've only focussed on sensors that are able to deal with the detection of objects around the host vehicle. Other sensors (for example a GPS) are also required but have nothing to do with detection, therefore we will not concider these.

4.2.1 Vision

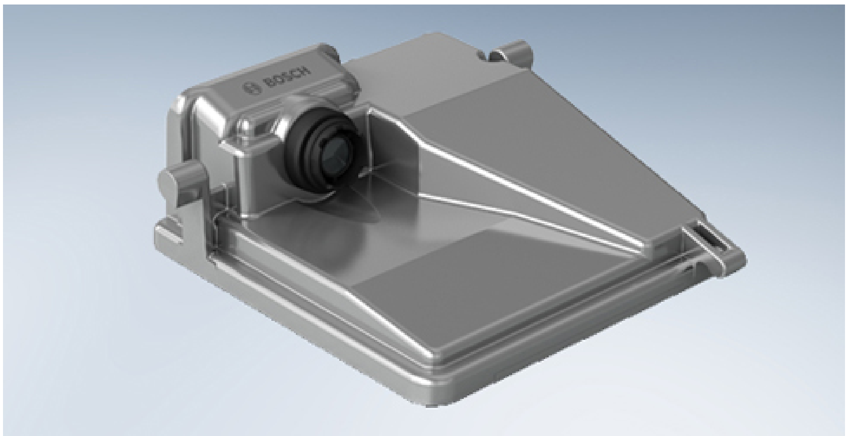


Figure 4.10: A monoscopic vision system (source: Bosch)

A vision system uses a light-sensitive sensor to form an image of the surroundings. Some highly important aspects of driving can only be sensed through a vision system, for example a sign could be detected by a number of different sensors, but the actual image on the sign can only be perceived using a vision system. Vision systems take advantage of the visual light spectrum (although some sensors are also able to pick up parts of the infrared spectrum, which allows for night vision [35]). A vision sensor requires an unobstructed line of sight, which means it has to be placed in open air or behind a translucent surface (i.e. the wind shield).

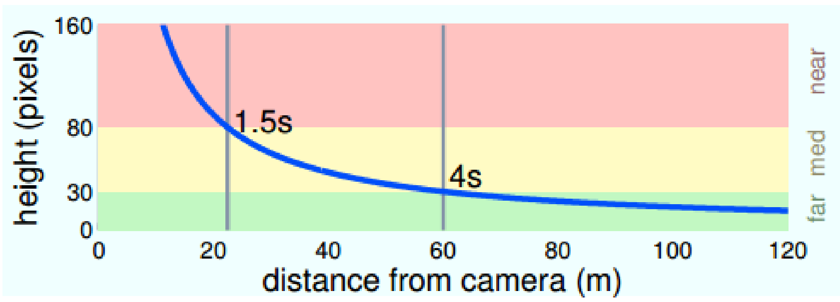


Figure 4.11: Relation between distance and height of a pedestrian in pixels (source: [27])

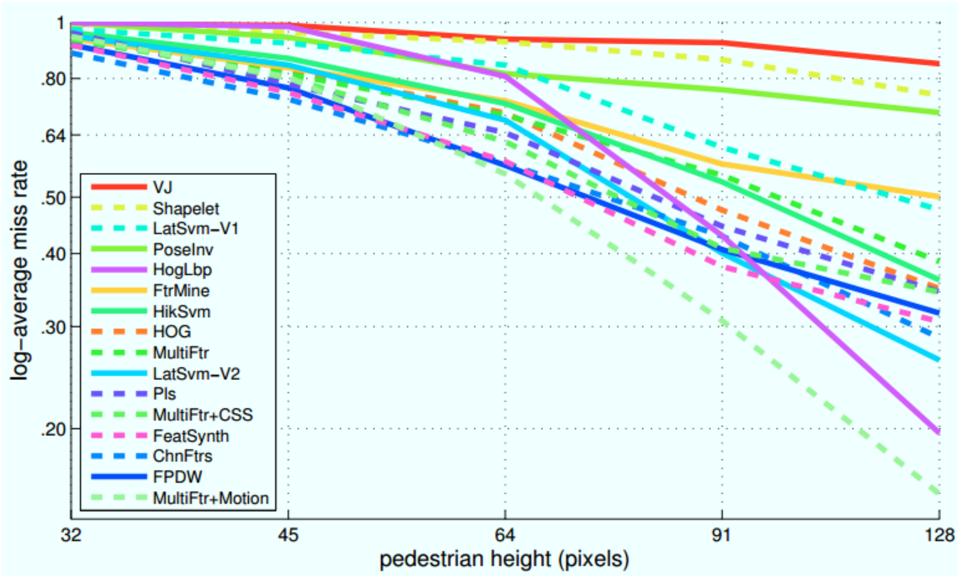


Figure 4.12: Relation between miss rate and pedestrian height in pixels (source: [27])

A vision system relies on image processing algorithms to detect and classify objects. Image processing is a demanding process but the information that can be extracted from images is very useful and can be used for many tasks like mapping and navigation, object detection and recognition, collision detection and more [51]. The processing algorithms used heavily influence the performance of a vision system. If we concider the pinhole camera model, an object's width and height in pixels is inversely proportional to its distance to the camera [27], as illustrated in figure 4.11. The work of [27] has described the relationship between a collection of state-of-the-art pedestrian recognition algorithms and the height of a pedestrian in pixels, as shown in figure 4.12. The further away a pedestrian is, the smaller its size in pixels will be, hence the chance of a pedestrian going undetected increases. An obvious conclusion is that a high resolution is beneficial, which was also mentioned by [27]. A slightly more disturbing conclusion is that pedestrian detection using vision alone is not very reliable, even when using the best algorithms currently available [35] [27]. Fusion of vision systems with RADAR and LIDAR sensors has the potential to improve pedestrian detection performance [34], but this is still an open area of research [35]. Sensor fusion (mainly RADAR and vision) has been applied to vehicle detection, with good results [53].

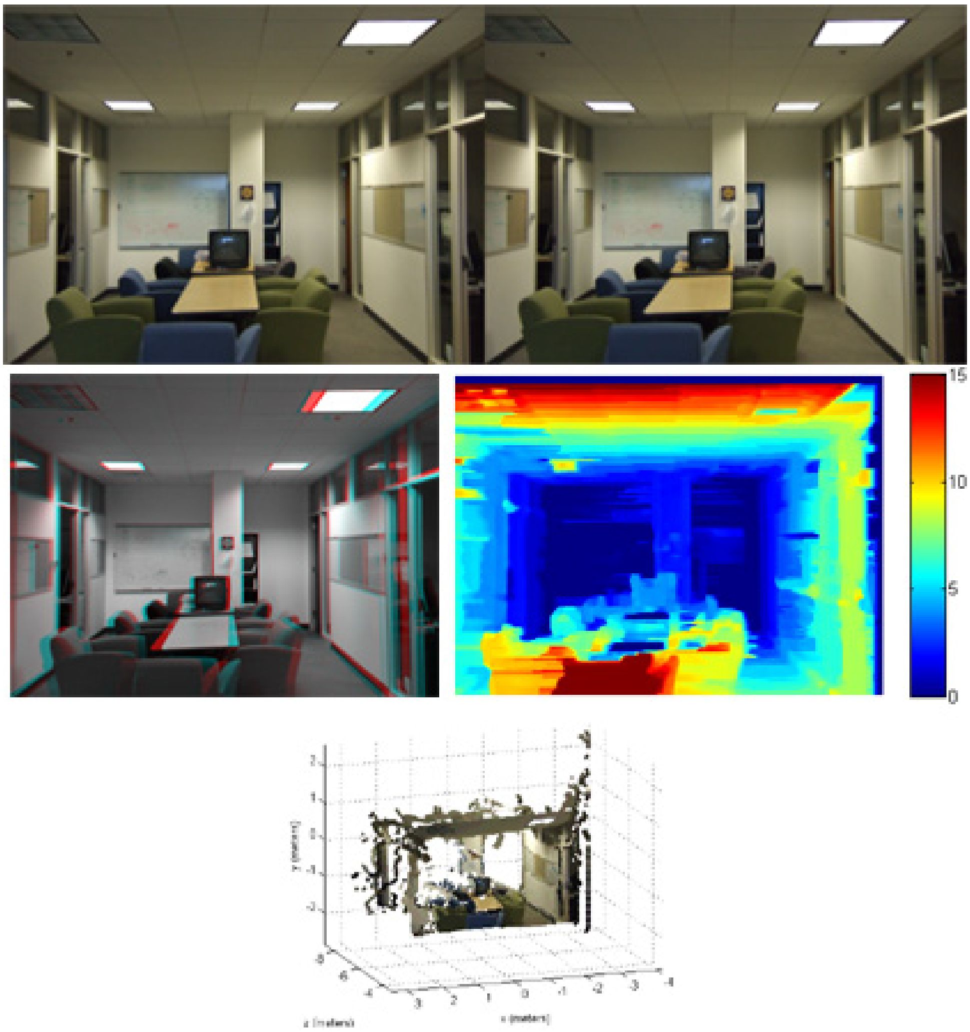


Figure 4.13: Stereo camera: left and right image (top row), composite image (middle-left), disparity map (middle-right), and the rendered 3D scene (bottom) (Source: mathworks.com)

Two main types of vision systems can be distinguished: monoscopic, and stereoscopic. Monoscopic vision systems simply use one optical sensor. Stereoscopic vision systems consist out of two optical sensors with a small distance between them. Similar to a pair of human eyes, this allows depth perception. Stereo vision uses disparity (the difference in position of a point or area between the left and right image) to calculate a depth image. Figure 4.13 shows such a disparity map. The accuracy of this depth image decreases greatly with distance since the disparity is much lower for points that are far away from the sensor [51]. According to [24], the stereo systems on their vehicle are only effective up to 40 m.

Figure 4.14: Degraded performance during heavy rain (source: carsut.com)

Figure 4.15: Degraded performance in foggy conditions (source: hessertoyota.com)

Visions systems are passive, which means their performance depends on external lighting conditions. Low lighting conditions occuring at night can degrade the performance of the sensor. High-intensity lighting conditions, such as a setting sun or bright headlights of an oncoming vehicle can also blind a vision sensor. Another major influence on a vision sensor's performance is the weather. Heavy rain, snow and especially fog can greatly decrease the effective range of the image processing algorithms, as can be seen from images 4.14 and 4.15.

Most of the automotive vision systems currently available are multi-purpose units, and come with a built-in image processor. The unit is usually equipped with a number of algorithms for different detection and classification purposes, such as Traffic sign Recognition, Pedestrian detection, General object detection and Light spot Detection (used for adaptive lighting). As mentioned earlier, the detection and recognition performance is heavily influenced by the quality of the imaging sensor and the algorithms used by the processing unit.

Advantages

- Can classify objects, detect lane markers, read signs, etc.
- Large Field-of-View (FOV)

- Passive, so systems can't interfere with eachother
- Usually comes with on-board algorithms

Disadvantages

- Requires heavy processing (especially stereoscopic vision systems)
- Range and performance depends on algorithms
- Affected by lighting and weather conditions
- Requires a clear line-of-sight

Vision sensor COTS comparison

								Range (m)		FoV (deg)										
Make/Model	Type	Stereo gap (m)	Hres (pixel)	Vres (pixel)	Imager Res (MP)	Focal length (mm)	pixel size (um)	Range (m)	Accu (m)	H.Angle (deg)	V.Angle (deg)	Angle Acc (deg)	Wave Length (nm)	Speed Range (km/h)	Dynamic Range (dB)	Imager	fps	Rate (Hz)	Interface	Remarks
Continental MFC2	mono		752	480				500	±10 (r<150m)	35	23		410 - 720	0 - 162	110			16	CAN	
									±50 (r>150m)											
Continental Stereo	stereo	0.2							0.3 (r<30m)							CMOS				
Bosch MPC	mono		1024	512	0.5	6.9	5.6 x 5.6	2.5 - 400		41	19				120	CMOS	25		CAN/FlexRay	image output
Bosch Stereo	stereo	0.12	1280	960	1.2			>50		45	25					CMOS				
Delphi IFV100/200/	mono									45	29					CMOS				IFV200 can be fused with delphi RADAR
TRW Scalable	mono							80		42		4		260						Can be fused with TRW radars.
Mobileye	mono		752	480			6 x 6			38					60	CMOS	60		CAN	
Melexis MLX75403	mono		640	480		5.5	8 x 8			54			470 - 1050		120	CMOS	60		composite, I2c	Visible & NIR, Imager only
Vislab 3DV *	stereo	0.4	1280	960				1.8 - ...	1 @ 22 m	66								10	Ethernet (UDP)	

* Multiple configurations available, specs vary slightly

4.2.2 LIDAR

Figure 4.16: A LIDAR sensor (source: Ibeo)

A LIDAR sensor (a.k.a. laser scanner) is an active optical ranging sensor. Some of the applications are obstacle detection, pedestrian and vehicle detection [68] [32], lane recognition [63], and determination of the exact position of the vehicle [15]. It emits light pulses at a high frequency using a laser. If the emitted light hits and object, the reflected light is measured and used to calculate the distance between the sensor and the object. Since the laser can only measure a single small point at a time, the LIDAR has to measure at a high frequency to build up a high resolution depth image at the desired update rate. Meanwhile, the laser beam is aimed using rotating mirrors or by rotating the entire sensor unit. Automotive LIDARs typically scan in horizontal direction, which is done in layers. A larger number of layers allows the LIDAR to compensate for the pitch angle of the vehicle more easily [32], and reduces the influence of occlusions [59]. Currently available LIDAR sensors use up to 64 layers simultaneously. The range of a LIDAR can be over 250 meters, and the FOV can as large as 360 degrees. Unlike RADAR, LIDAR sensors can have a large FOV and range at the same time.

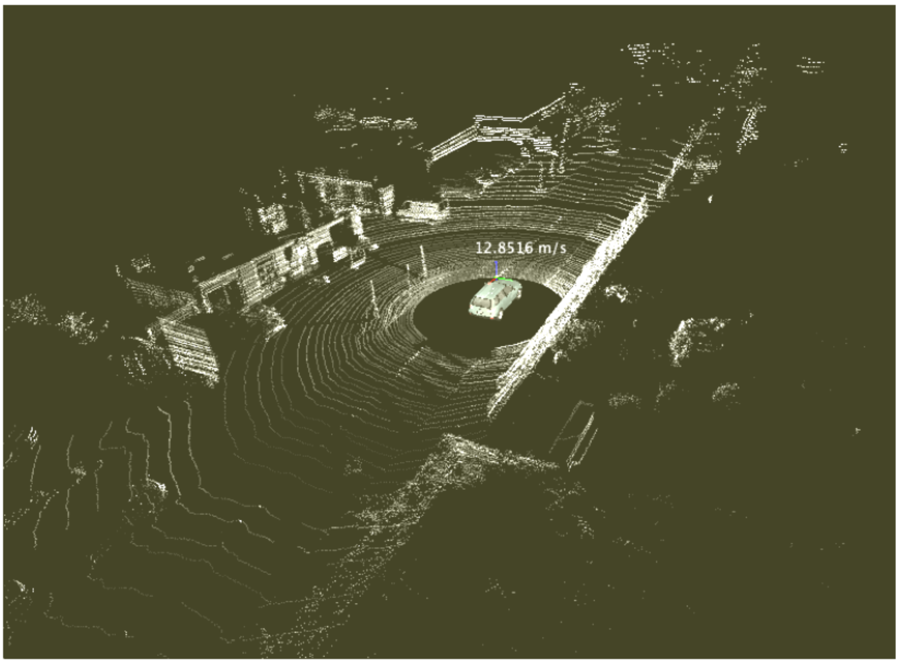


Figure 4.17: Point cloud generated by a 64-layer Velodyne LIDAR (source: [44])

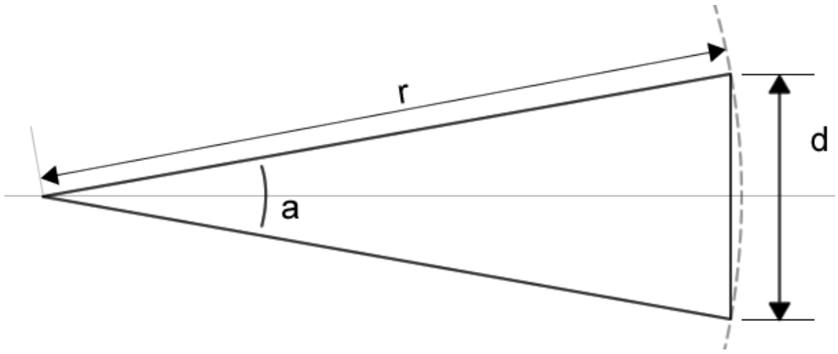


Figure 4.18: Seperation of two LIDAR points at a given range

The LIDAR generates a point cloud, where every point respresents a single distance measurement. An example of such a point cloud is shown in figure 4.17. This point cloud has to be processed in order to extract object information. Classification algorithms can be used to classify the detected objects [44]. To detect an object reliably, it is necessary to have at least two lidar returns from that object [81]. Given an angular resolution a and a range r, the distance between two LIDAR points d (illustrated in figure 4.18) can be calculated using the following equation:

$$d = 2r \sin(a/2) \tag{4.13}$$

Since $r \gg d$, this reduces to:

$$d = ar \tag{4.14}$$

In order to be able to see an object of size l at range r, the object has to be at least $2d$ wide to guarantee two LIDAR returns, assuming single layer scanning. This means that larger objects can be detect further away compared to smaller objects. LIDARs typically have a high angular resolution, which allows even small objects to be detected at fairly large distances. The angular resolution required to detect an object of size l at range r can be described using equation 4.15, which is confirmed in [81]:

$$a = \frac{l}{2r} \tag{4.15}$$

LIDARs can't detect velocity information directly. Tracking algorithms have to be used to analyze the position of an object over time, which allows the velocity to be estimated [55]. This is done by comparing two (or more) consecutive LIDAR readouts. Some algorithms incorporate a filtering process called gating [32], which reduces the area that is used to associate an between the readouts. This reduces unnecessary calculations, but it also means that a fast-moving object could end up outside the gated region [81], which means it would be interpreted as a 'new' object and tracking (and therefore velocity estimation) would fail.

Like vision systems, LIDARs are affected by adverse weather and lighting conditions [28], however 'multi-echo' technology can improve performance in these conditions by evaluating multiple LIDAR returns [73]. A clear line-of-sight is required, which means the sensor has to be placed in the open air or behind a transparent surface. Under good conditions, LIDARs can have a large range (over 200 m). Another important factor that influences the range is the reflectivity of an object. A object with high reflectivity can be detected at full range, but objects that reflect poorly can be detected at a significantly lower range. For example, the ibeo LUX system has a range of 200 m, but this range drops to 50 m for objects with a reflectivity of 10 %.

Most LIDARs have a very high resolution and accuracy specifications on paper, however manufacturers are very unspecific about whether these numbers apply to the point cloud data or to the interpretated object detection data (if there's any on board processing). The quality of the LIDAR data is only as good as its object recognition algorithms, and some accuracy is likely to be lost during this stage. Due to the sheer volume of data typically generated by LIDAR sensors, concessions often have to be made when it comes to processing, possibly decreasing the accuracy even further. These things should be checked and taken into account when deciding on buying a specific LIDAR sensor.

Lasers can be harmful to the humans and animals, especially to the eyes. Like all laser products, LIDARs are subjected to regulations defined by IEC 60825-1 [18]. This puts a limit on the LIDAR range, which (among other factors) depends on the power of the emitted pulse [54]. Most LIDARs are class 1 laser products, which means they are completely safe under normal operating conditions.

Advantages

- Long range
- Large FOV
- High angular resolution

Disadvanges

- Affected by weather and lighting conditions
- Requires a clear line-of-sight
- Poorly reflecting objects can't be detected at full range
- Velocity detection requires tracking
- Limited laser power due to regulations

LIDAR sensor COTS comparison

Make/Model	Layers	FOV		Range			Angle res (deg)	Speed			Rate (Hz)	Interface	Remarks
		Hor (deg)	Vert (deg)	Range (m)	Res (m)	Accu (m)		Range (km/h)	Res (km/h)	Accu (km/h)			
ibeo Lux 4 Layer	4	110 @ 2 Layers, 85 @ 4 layers	3.2	0.3 - 200	0.04	0.1	0.125				50	CAN	
ibeo Lux 8 Layer	8	110	6.4	0.3 - 200	0.04	0.1	0.125				25	CAN	
ibeo Lux HR / 16L	8/16	90	6.4	0.3 - 250	0.04		0.1				50	CAN	
ibeo Scala	4	145	3.2	0.3 - 327	0.04	0.1	0.25			0.9	25	CAN/Ethernet	range 150 for vehicles, 50 for pedestrians
ibeo MiniLux	1	180	1	0.05 - 40	0.04		1				5	Ethernet	range 40 for vehicles, 15 for pedestrians
Sick LD-MRS400001	2	110		0.5 -250			0.125				50	Ethernet/RS232/CAN	Tracks up to 128 objects
Sick LMS151	2/4	270	3.2	0.2 - 50	0.2		0.5				50	Ethernet/RS232	
Continental SRL 1	3	27	11	0 - 13.5	0.001	0.1		2 - 160	1	2	100	CAN	
Denso	6	36	8	0 - 120		0.01	0.08				10	CAN	
Velodyne HDL-64E	64	360	26.8	0 - 120		0.02	0.09				15	Ethernet	
Velodyne HDL-32E	32	360	40.67	1-100		0.02					10	Ethernet	

4.2.3 RADAR

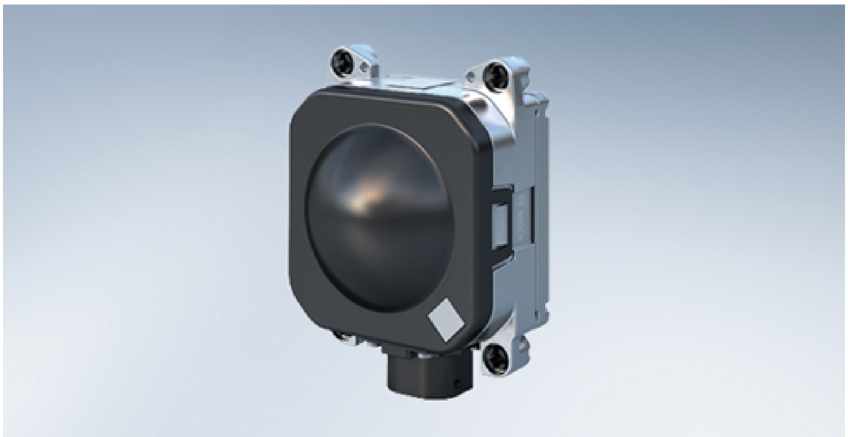


Figure 4.19: An automotive RADAR sensor (source: Bosch)

RADAR sensors work by emitting high-frequency radio signals, and measuring the reflection of that signal coming from any present object(s) within the sensor's FOV. RADAR sensors are also able to directly detect the relative velocity of a detected object. RADAR sensors can have a large FOV and range, but a tradeoff has to be made [64]. The energy of a RADAR signal can be distributed over a large FOV, but this spreads out the energy of the signal which results in a smaller range. Some RADAR units can dynamically change the FOV (together with the range) during operation.

There are two main frequency bands used by automotive RADAR sensors, the 24 GHz band and the 77-81 GHz band. The 24 GHz is mainly used by older RADAR types, and used to be popular because of readily available microwave components from the telecom industry[72]. The 24 GHz band is no longer allocated for automotive use since june 2013 [86], and development has shifted towards 77-81 GHz. This frequency band provides superior range, resolution and accuracy due to it's shorter wavelength compared to 24 Ghz, which makes it more suitable for applications such as pedestrian detection.

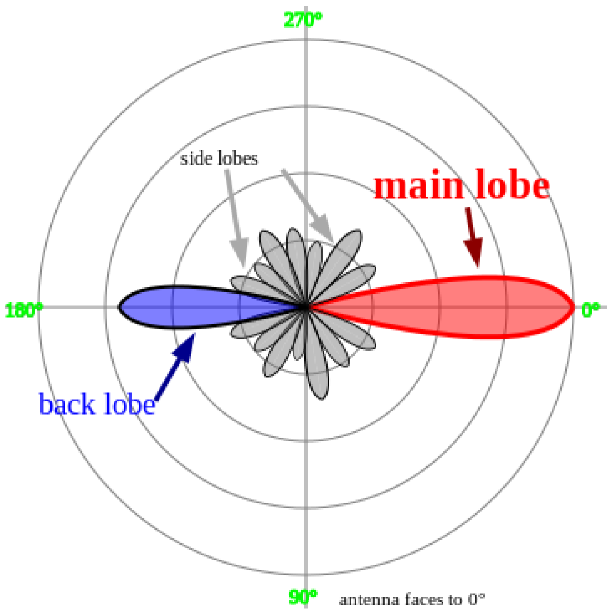


Figure 4.20: Lobes emitted by a RADAR sensor (source: wikipedia)

Figure 4.20 shows how the RADAR sensor emits its energy. Apart from the main lobe, smaller sidelobes (and a back lobe) appear around the transceiver. These sidelobes can be suppressed, but can never be completely eliminated. They can cause noise which negatively affects detection ability in the main lobe. Due to these sidelobes, RADAR sensors are not accurate at close proximity (under 1 meter).

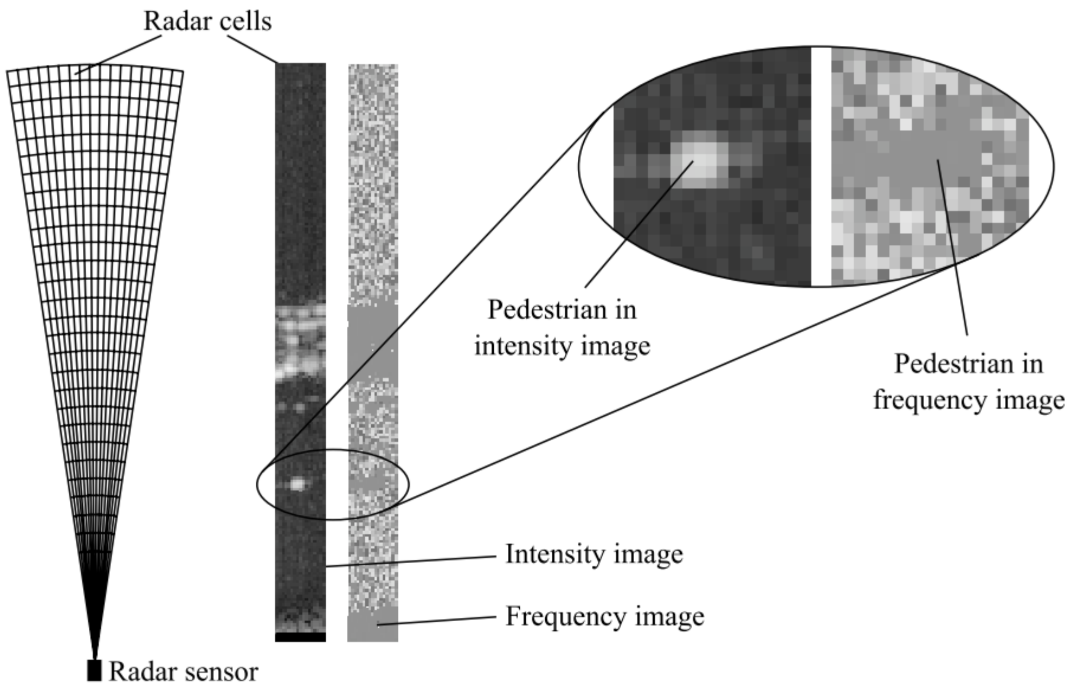


Figure 4.21: Resolution cells within a RADAR beam (source: [10])

RADAR sensors commonly have good distance resolution and accuracy, especially 77-81 GHz devices. The angular resolution and accuracy are usually lower, and a wider FOV usually means a lower angular accuracy and resolution. The detection area of a RADAR sensor is divided into resolution cells, as shown in figure 4.21. The size of a resolution cell is determined by the angular resolution and the range resolution. The length of a cell stays the same, but the width increases with range. Through small angle approximation, the width w of a cell of a RADAR with angular resolution a (in radians) at range r can be described using equation 4.16 [20] (see figure 4.18 and equation 4.13 for a more thorough explanation).

$$w = a \cdot r \tag{4.16}$$

For each cell, the intensity of the reflected signal and the doppler frequency shift of that signal is measured, which allows for direct measurement of the range and relative velocity. The range and angular resolution of a RADAR cell are important factors for the discrimination of multiple targets [23]. Unless one can rely on eventual different Doppler shifts, it is impossible to distinguish two targets which are located inside the same resolution cell [89]. It should also be noted that a nearby object can occlude objects further away if the near object blocks the line-of-sight.

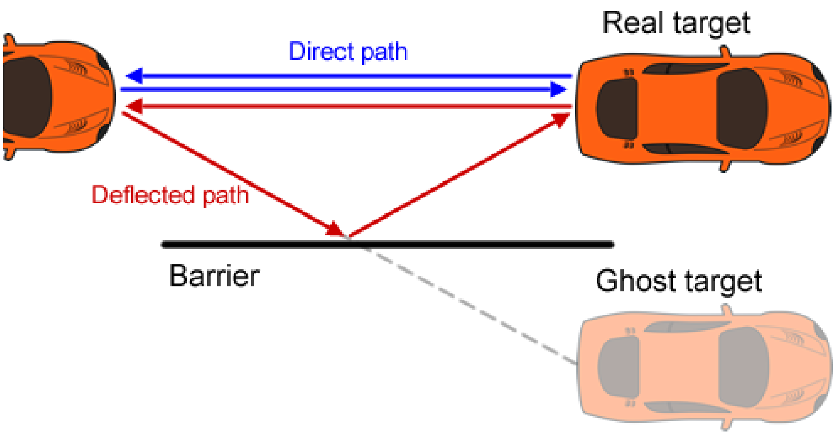


Figure 4.22: Ghost target generation due to deflection of the RADAR signal

Another problem of RADAR sensors is the possiblity of generating ghost targets. They can appear when the RADAR signal reflects off more than one object before being received back by the sensor unit. This can cause the detection of a non-existing target at a random position. An example is shown in figure 4.22. These ghosts targets can be hard to distinguish from real targets. Sidelobes can also cause ghost targets to appear. A common technique to solve this problem is to fuse the RADAR data with information from other sensors, such as a vision system.

RADAR sensors are susseptible to interference caused by other emitting radar sensors. One radar might pick up the other's signals, causing false detections and lowered signal-to-noise ratio [36]. This has been an issue in busy marine environments, and it could become a problem in daily transportation as more and more vehicles are being equipped with RADAR sensors. An effective interference reduction technique is Noise Radar Technology (NRT). The emitted signal's waveform is based on pseudo-randomly generated noise. This effectively codes the waveform, making it unique and distinguishably from any other incoming signals [33].

Advantages

- Long range (at the cost of FOV)
- Large FOV (at the cost of range)
- High range accuracy
- Direct relative velocity detection
- Unaffected by weather and lighting conditions
- Does not require a direct line of sight, can be mounted behind 'RADAR-transparent' materials

Disadvanges

- Tradeoff between range and FOV
- Does not work well at very short range (<1 m)
- Ghost targets
- Low angular resolution / accuracy
- Possible interference with other RADAR sensors

RADAR sensor COTS comparison

				Range (m)			H.Angle (deg)			V. Angle	Speed							
Make/Model	FoV & Range	Freq (GHz)	BW (MHz)	Range (m)	Res (m)	Accu (m)	Range (deg)	Res (deg)	Accu (deg)	Range (deg)	Range (m/s)	Res (m/s)	Accu (m/s)	Rate (Hz)	Interface	max # targets	Cycle time (ms)	Remarks
Continental ARS308	Dynamic	76 - 77		0.25 - 200	2	0.25 or 1.5% > 1m	±8.5	1	0.1	4.3	-24,4 - +73,6	0.77	0.13	15	CAN	90	66	
				0.25 - 60			±28	4	1-2			1.53	0.28					
Continental SRR 208	Static	24		1 - 50	1	0.2	±20	14	2	±6	-40,5 - + 40,5	0.3	0.05	26	CAN		38	
							±75	18	5									
Bosch MRR plus	Static	76 - 77	500	1 -160			±22.5								CAN			
Bosch MRR base	Static		500	1 - 120			±30											
Bosch LRR3	Static			0.5 - 250		0.1	±15*			±2.5	-75 - +60		0.12	32	CAN / FLEXRAY	32	80	
Bosch MRR rear	Static	76 - 77	500	0 - 100			±75		0.8					15				
Delphi ESR	Static	76.5		1 - 174		0.5	±10		0.5	4.2 - 4.75	-100 - +25		0.4	20		64	50	Dual beam
				1 -60			±45											
Delphi RACAM	see Delphi ESR																	Integrated ESR Radar/Camera
Delphi RSDS	Static	76.5		0.5 - 70			±75			±5								
							±40											
TRW AC3		77		0 - 250														
TRW AC100		24	100	0 - 150			±12	2.5	0.5		up to 70	0.38						
							±8											
TRW AC1000		79		0 - 70														
SmartMicro UMRR type 29	Static	24		1 - 160		0.25	±18			±4				20	CAN	64		
SmartMicro UMRR type 30		24		1 - 90		0.25	±35			±5					CAN	64		
SmartMicro UMRR type 31		24		1 - 45		0.25	±50			±5					CAN	64		
Denso (new model)		79		0 - 205			±10											Dual beam
				0 - 35			±18											
Denso (old model)				0 - 151			±10											

* can be modified to ±22.5 according to datasheet

4.2.4 Ultrasonics

Figure 4.23: An ultrasonic sensor (source: Futurelec)

Ultrasonic sensors operate by emitting a high-frequency audio signal, which will reflect off any object in front of the sensor. This reflected signal is detected, and the time difference between sending the signal and receiving the reflected signal is used to calculate the distance to the object. Ultrasonics are commonly used as parking sensors in modern cars.

Since ultrasonics use an audio signal, their performance could be degraded if the air carrying the signal is moving. The faster the vehicle is traveling, the faster the airflow around the car body will be, possbily creating vortices as well. In [65], an ultrasonic sensor is used to measure the distance of a car underbody w.r.t. the road surface. Their system was tested with speeds up to 120 km/h, and performed well for all typical driving maneuvers, so we can assume that ultrasonic sensors can operate at least up to highway speed limits.

Ultrasonic sensors are active, they rely on a internally generated audio signal to perform their measurements. This would mean that they could also pick up signals from other ultrasonic sensors. This problem is similar to the RADAR interference problem, and the solution posed [87] is also similar. It uses stochastic coding of the signal, so it can be distinguished from other signals using an adaptive filter. This technique is similar to Noise Radar Technology, and has been able to effectively solve the interference problem.

Advantages

- Simple sensor, reliable
- Low-cost and readily available
- Able to detect extremely close objects

Disadvantages

- Low range
- Wind effects could become a problem at high speeds
- Can interfere with other ultrasonic sensors

Ultrasonic sensor COTS comparison

Ultrasonics are available from as OEM products and aftermarket kits. There are simply too many products available to perform a COTS comparison. We have listed a few commonly available sensors which will give us a good idea of the typical specifications of the average ultrasonic sensor.

Make/Model	Freq (kHz)	Range (m)	Accu (m)	H.Angle (deg)	V.Angle (deg)	Remarks
Bosch	48	0.25 - 4		120	60	also available as aftermarket kit
Autosonar		0.4 - 1.5	0.01	80	80	aftermarket kit

4.2.5 Night Vision

Night Vision has been discussed as an ADAS system, see section 3.6.

Advantages

- Temperature-sensitive detection (FIR)
- Early detection of pedestrians, cyclists and animals (NIR & FIR)
- Drivers are not blinded by active IR beams (NIR)

Disadvantages

- NIR systems can blind FIR systems and other NIR systems
- Wide-spectrum lightbulbs can blind the system
- FIR systems can't detect objects close to environment temperature

Night Vision COTS comparison

Very little information is available about the specifications of automotive Night Vision systems. These systems are produced directly for large car manufacturing companies, hence these systems are merely showcased on the websites of the night vision system's manufacturer.

Make/Model	Type	Range (m)	Used by	Remarks
Autoliv	FIR	100	AUDI, BMW, Rolls Royce	Animal detection
Autoliv	NIR + FIR	150	Mercedes	Dual camera. Animal detection
Bosch	NIR	150	Mercedes	

It should be noted that the range of the system is not a hard limit, but rather a distance at which the driver is now able to detect objects on the display of the system.

4.2.6 Time-of-Flight

Figure 4.24: Human face captured by a time-of-flight camera (source: wikipedia)

Time-of-flight sensors (a.k.a. Photonic Mixer Devices or PMD's) are relatively new, and utilize the LIDAR principle: a pulse is fired, and the amount of time it takes for the pulse to reflect and travel back to the sensor is measured [61]. Instead of doing this repeatedly with a small linear laser pulse, like a LIDAR does, a larger single pulse is fired. The reflection is not measured for a single point, but for the whole field-of-view at the same time. This allows for faster operation and the absense of moving parts.

Some ToF sensors can detect both light intensity and depth information simultaneously. Stereo vision systems can also derive depth information, but it requires heavy processing. ToF camera's are able to measure this depth information directly.

Advantages

- Simultaneous depth and intensity measurement
- Fast operation

Disadvantages

- Not readily available
- Affected by weather and lighting conditions

Time-of-flight COTS comparison

At the moment, the only known TOF automotive sensor is the SenseAhead system which is currently being developed by a luxembourg based company called IEE. The systems uses a state-of-the-art camera and a lower resolution TOF imager to produce the depth image, and the TOF imager is fully immune to sunlight interference. No information is available about the specifications.

4.3 Sensor fusion

Sensor fusion is the combining of sensory data collected from different types of sensors, which can enhance the perception abilties of an automated vehicle [68]. Sensor fusion can help to overcome certain drawbacks of other sensors, by fusing it with a different sensor that does not have this drawback. A common example is the fusion of RADAR and vision. RADAR sensors typically have high distance resolution but have low angular resolution, which can cause issues with object discrimination at larger distances. Vision systems typically have a large angular resolution, but have no depth information (or limited, in case of a stereo vision system). By combining a RADAR and vision sensor (see figure 4.25), we get a large detection range with good angular and distance resolution [13]. In [13], the object detection of the RADAR is used to identify regions-of-interest (ROIs) for the vision system, after which the vision system applies a vehicle recognition algorithm to these ROIs, to verify and classify the objects detected by the RADAR. A similar system can be constructed using LIDAR and vision system, as was done by [68]. The LIDAR is used to detect objects and identify ROIs, which are then processed by the vision system.

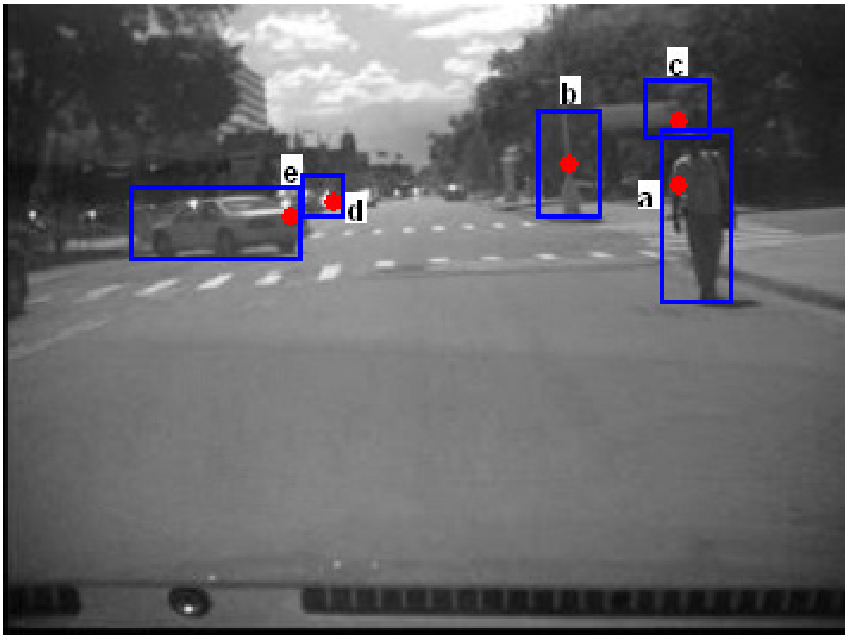


Figure 4.25: Example of RADAR and vision fusion (source: http://www.cse.msu.edu)

Chapter 5

Highway analysis

Highways (also referred to as motorways) are high-capacity roads that allow traffic to move at high speeds. Most highways have a speed limit of 130 km/h or less, although some exceptions exist (i.e. the German 'Autobahn' highway system, where there is no speed limit). Traffic moves unidirectionally on one or more lanes, while opposing traffic is separated typically by a barrier and/or a strip of land. Entry strips allow traffic to accelerate and merge with other highway traffic, and exit strips allows vehicles to leave the highway. Usually an emergency lane is present to accommodate emergency services or broken down vehicles.

Figure 5.1: A typical highway road (source: Google Streetview)

Every country has certain rules and guidelines on how to design and construct roads. In our analysis we will mainly use the guidelines used by the Dutch Ministry of Transport [7]. The Dutch highway system has a speed limit of 130 km/h, which is the limit in the majority of other countries as well. We will concider design speeds of 80, 100, 120 and 130 km/h for our analysis. Highways in most countries are intented for motor vehicles only, i.e. passenger vehicles, freight trucks, busses, motorcycles, etc. For convenience and in accordance to Dutch law, we will assume that no pedestrians, cyclists or animals will be present on highway roads.

Road geometry

Highway roads typically consist out of one or more lanes, typically 3.5 m wide [7]. For our calculation we will assume that all highway lanes are 3.5 m wide. Highways are designed with little curvature and smooth transitions between differently curved sections. For sections with constant curvature, the Dutch Ministry of Transport has defined the following minimum radii [7]:

Design velocity [km/h]	Minimum curve radius [m]
120	1500
100	800
80	400

Table 5.1: Minimal curve radius versus design speed

Unfortunately, a maximum speed of 130 km/h has only been recently introduced in the Netherlands and the document has not been updated accordingly. However, by looking at the numbers in table 5.1 and considering the fact that centrifugal forces increase at higher velocities, we can conclude that the smallest radius for 130 km/h must be at least equal to 1500.

For transitions between differently curved sections of road, a clothoid model (a.k.a. Euler spiral) is typically used to describe the curvature such smooth transitions [60] [7]. A clothoid provides a smooth transition between a curve A and curve B. The curvature of the clothoid will never be smaller than the curvature of either curve A or B, depending on which one of the two has the smallest radius, hence the clothoid radius will never become smaller than the values listed in table 5.1. Because of this, we will only concider circular road elements from now on, since these represent the most challenging curvature.

Road users

Only motor vehicles such as passenger cars, trucks, busses and motorcycles are allowed to use the highway, although rules differ from country to country. In our analysis, we will assume that we will only be dealing with motorcycles, passenger vehicles and bigger vehicles such as busses and trucks. Motorcycles are the most narrow vehicles we can encounter on the highway. Our criterium to determine the required sensor accuracy is based on the vehicle width and the assumption that all vehicles stay within their lane boundaries unless they deliberately want to change lanes (see section 4.1.4). Therefore we will use the maximum error values for motorcycles (table 4.1) to define our requirements for the allowable measurement error.

Lateral spacing

Vehicles tend to drift around laterally in their lane due to i.e. wind and correctional movements. In [7] it is mentioned that drivers tend to keep a minimum lateral distance of 0.5 m to 1 m to any vehicles on the adjacent lane, depending on vehicle speed (speeds between 50 km/h and 120 km/h are concidered). A similar conclusion can be drawn from data shown in [40]. Since we are only interested in speeds up of 80 km/h and higher, we will take the smallest value found for 80 km/h in [40], which is roughly 0.75 m, as can be seen from figure 5.2. This value, together with calculations described in section 4.1.4, is used to calculate the minimum angular resolution required to guarantee proper object separation (see section 4.1.2 for a more thorough explanation).

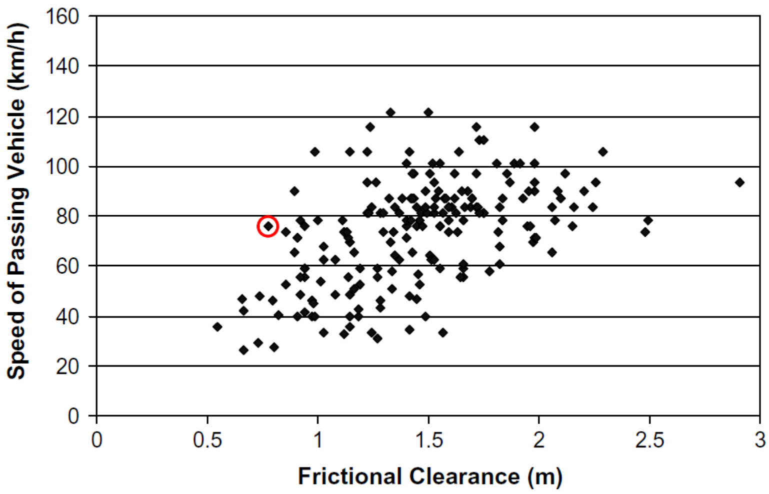


Figure 5.2: Lateral distance between two vehicles (named Frictional Clearance) at different vehicle speeds. The red circle indicates our chosen value (source: [40])

Deceleration, safety and comfort

In [76], a deceleration of 5 m/s^2 was used to calculate braking distances, assuming the suboptimal situation of a wet road surface. We will use this value to calculate emergency braking scenarios, where safety is a key factor. However, more regular maneuvers (i.e. headway keeping) occur much more frequently, hence these maneuvers require a certain degree of comfort. The limit of longitudinal comfort is 2 m/s^2 according to [90], which is the value we will be using for situations that require comfortable braking. Furthermore, in order to simplify things a little, we will assume that the host vehicle requires zero reaction time since it is an automated vehicle.

5.1 Scenario analysis

In order to analyze and define sensing requirements for highway driving, we decided to split it up in different scenarios which we will discuss separately. Each scenario poses a specific set of problems that an automated vehicle should be able to deal with. Based on earlier research [47, 42, 62, 9], the following scenarios were identified to be typical to a common highway trip:

1. Emergency stop
2. Maintaining a desired speed and safe headway, while staying in the current lane
3. Changing lanes
   (a) Entering the highway by merging into the traffic on the first lane.
   (b) Overtaking slower traffic
   (c) Exiting the highway

Entering the highway is essentially a lane change maneuver, except that the length of the access strip forces the vehicle to perform the lane change before the end of the strip is reached. Exiting the highway is another form of lane changing, however, if the desired lane change can't be performed before reaching the end of the exit strip, the exit will be missed and another route to the destination has to be chosen. We have decided to treat merging, exiting and overtaking as regular lane changes, and will evaluate them as such.

5.1.1 Emergency stop

If the road ahead is blocked by a stationary object (i.e. a crashed vehicle or the end of a traffic jam), the host vehicle should be able to perform an emergency stop in order to avoid a collision with the object. In this scenario we will only concidered stopping for objects in the path of the host vehicle. We will not concider vehicles behind the host vehicles, as it is their responsibility to maintain a safe headway distance to allow them to respond in time.

Metrics

Since we have assumed the highest highway speed to be at 130 km/h, the host vehicle should be able to perform a full stopping maneuver starting at 130 km/h. We can neglect the reaction time, as it is irrelevant to an automated vehicle. We will also neglect any limits that define human comfort, since an emergency stop is a rare event that is not intented to be comfortable, it is intented to keep the passengers safe. As discussed earlier in this chapter, we will use a deceleration value of 5 m/s^2 for our calculations, which allows us to calculate the range values shown in table 5.2. These calculations are described in detail in section 4.1.

Design speed [km/h]	Range [m]	Max ang. error [°]	Min ang. resolution [°]
130	131	0.14	0.33
120	112	0.16	0.38
100	78	0.24	0.55
80	50	0.37	0.86

Table 5.2: Required values for the forward-looking sensing for the 'emergency stop' scenario

Detection coverage

The stationary object that poses the collision threat can either be present on the current lane or on any of the adjacent lanes, or even on multiple lanes. In some cases an emergency stop could be prevented by performing a lane change maneuver, while in other cases the vehicle should just break and stay in the current lane. In order to be able to make a decision on this, both adjacent lanes and the current lane have to be covered.

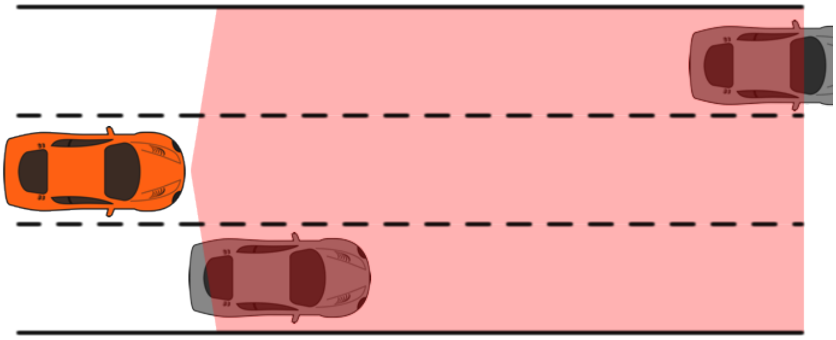


Figure 5.3: Required forward-looking detection coverage for the 'emergency stop' scenario

5.1.2 Maintaining speed / headway

The host vehicle should be able to maintain a desired fixed speed, while also maintaining a safe headway to the lead vehicle. The worst-case scenario would a situation where be the host vehicle is travelling at 130 km/h while the lead vehicle has stopped completely. This case is already covered by the emergency stop scenario discussed earlier, however human comfort was not taken into account since an emergency scenario is a rare event. Headway keeping however is a constant control process, and we want this to happen comfortably.

Metrics

According to [85], the 90th percentile of relative speed between two adjacent highway lanes is 30 km/h or less, based on real vehicle measurements. For our calculations, we assume that no vehicles will have a relative speed larger than 30 km/h. In the literature a comfortable longitudinal acceleration limit of 2.0 m/s^2 has been defined [90], which we will use in our calculations. The calculations used are described in detail in section 4.1.

Design speed [km/h]	Range [m]	Max ang. error [°]	Min ang. resolution [°]
130	134	0.14	0.32
120	122	0.15	0.35
100	99	0.19	0.43
80	76	0.24	0.57

Table 5.3: Required values for the forward-looking sensing for the 'maintaining speed / headway' scenario

Detection coverage

In order to track the lead vehicle, the system needs detection coverage on the current lane. In order to anticipate on vehicles cutting in, coverage of the adjacent lanes is beneficial. The detection coverage shown for the 'Emergency stop' scenario (see figure 5.3) is sufficient to cover this scenario.

5.1.3 Changing lanes

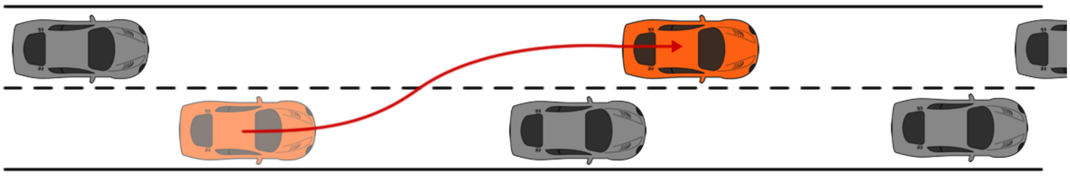


Figure 5.4: A lane change maneuver

A lane change is the only highway maneuver that involves lateral movement between adjacent lanes. In order to ensure a safe lane change maneuver, there must be a sufficiently large distance between several vehicles:

- Vehicles approaching from the rear in the target lane and current lane. A fast-approaching vehicle at a short distance could lead to a rear-end collision with the host vehicle.
- The leading vehicle in the current lane. The host vehicle should keep a safe distance until the lane change has been completed.
- Leading vehicles in the target lane. If this vehicle is slowing down for some reason (i.e. a traffic jam), the maneuver might have to be aborted.
- Vehicles immediately next to the host vehicle. These would simply block the path of the host vehicle as it is traveling to the adjacent lane.

Forward-looking vehicle detection has been discussed in scenario 1 and 2, hence we will only focus on backward and lateral detection in this section.

Metrics

In [85], it is shown that human drivers will cancel an intented lane change maneuver if the time-to-collision (TTC) w.r.t a vehicle approaching from the back is between 6 and 10 seconds. For a TTC small than 6 s all lane changes were cancelled, and above 10 s all lane changes were carried out. We decided to take the average value, 8 s, as our criterion to decide whether or not to carry out the lane change. Furthermore, as discussed in the Maintaining Speed / Headway scenario (section 5.1.2), we will assume that no vehicle will overtake the host vehicle with a speed larger than 30 km/h. The calculations used are described in detail in section 4.1.

<table>
<tr><th>Design speed [km/h]</th><th>Range [m]</th><th>Max ang. error [°]</th><th>Min ang. resolution [°]</th></tr>
<tr><td>130</td><td rowspan="4">67</td><td rowspan="4">0.27</td><td rowspan="4">0.64</td></tr>
<tr><td>120</td></tr>
<tr><td>100</td></tr>
<tr><td>80</td></tr>
</table>

Table 5.4: Required values for the backward-looking sensing for the 'changing lanes' scenario

If any vehicles are present on the target lane next to the host vehicle, a lane change maneuver simply can't be carried out as it would result in a collision. All that is required is a basic method of detecting the presence of any vehicles. Assuming that the host vehicle is at least 1.4 m wide and is driving in the center of the lane, we can achieve full coverage of both adjacent lanes using 4.55 m of lateral detection (assuming a 3.5 m lane width. See also figure 5.6). Angular resolution and error are irrelevant in this case.

Detection coverage

Figure 5.5 and 5.6 illustrate the required backward and lateral detection coverage required.

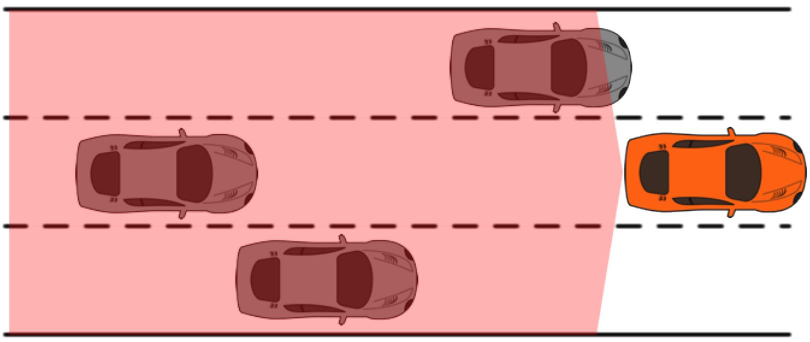


Figure 5.5: Required backward-looking detection coverage for the 'changing lanes' scenario

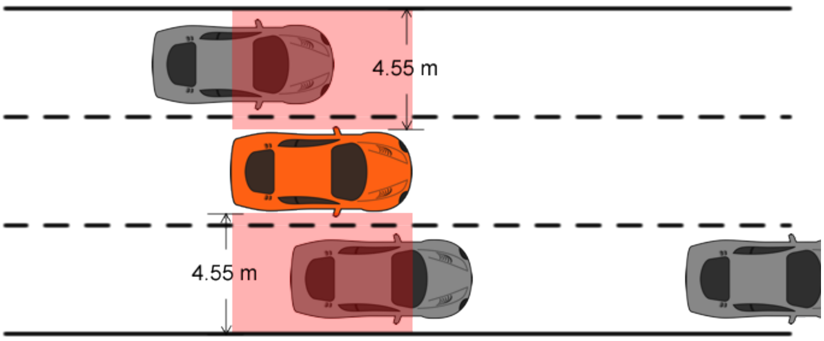


Figure 5.6: Required lateral detection coverage for the 'changing lanes' scenario

5.2 Requirements summary

This section provides a comprehensive overview of the sensor coverage and metrics required to cover all highway scenarios discusses earlier in this chapter. We will also present an exact plot of the required sensor coverage based on rules on road curvature design. The information presented in this section can be used as a tool to select an adequate sensor set.

5.2.1 Detection coverage

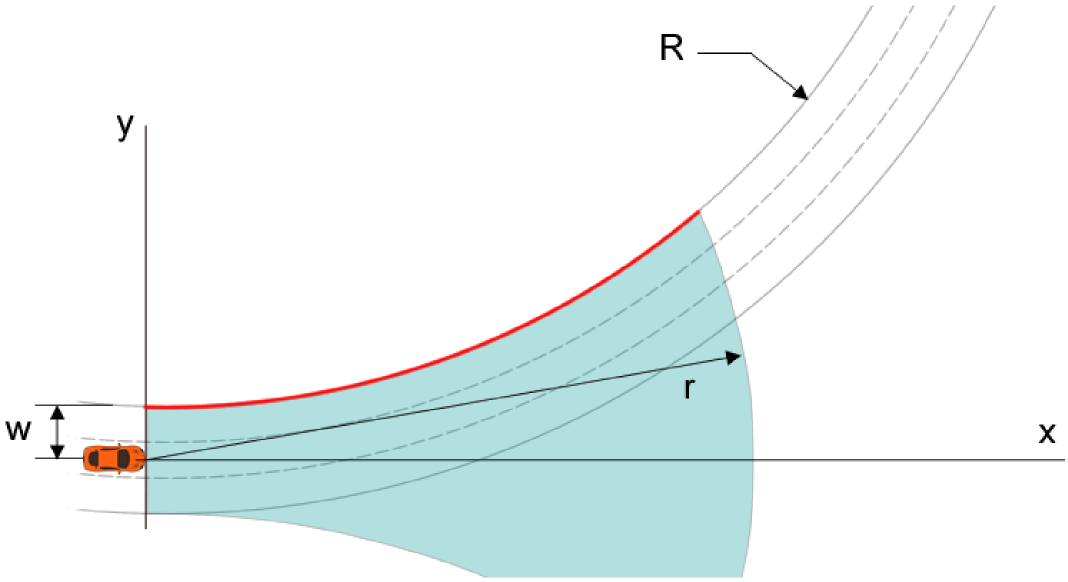


Figure 5.7: Coordinate system used to determine sensor coverage

In order to properly assess the total sensor coverage required we have to take road curvature into account. The required coverage depends on the required range and the amount of road curvature that we can expect on certain roads, as well as the required lateral distance we have to cover. From the scenarios discussed in this chapter, we can conclude that we need coverage of the ego lane and both adjacent lanes on either side of the vehicle. This is illustrated in figure 5.7. If we assume a circular road, then we can describe the y value of the red arc using:

$$y = w + R - \sqrt{R^2 - x^2} \tag{5.1}$$

Since $r^2 = x^2 + y^2$, x becomes:

$$x = \sqrt{r^2 - y^2} \tag{5.2}$$

By plugging equation 5.2 in equation 5.1, we get:

$$y = w + R - \sqrt{R^2 - r^2 + y^2} \tag{5.3}$$

Solving for y yields:

$$y = \frac{r^2 + 2Rw + w^2}{2(R + w)} \tag{5.4}$$

Equations 5.2 and 5.4 allows us to easily plot the required sensor coverage for any required sensor range and any required road curvature radius, concidering any offset w. We will assume that the host vehicle has efficient control algorithms that allow it to stay in the center of the lane for most of the time. This allows us to define w as 1.5 times the width of a highway lane ($w = 5.25$). Along with the ranges found for each scenario and the radii defined in table 5.1, we can create a plot of the required total sensor coverage, as shown in figure 5.8.

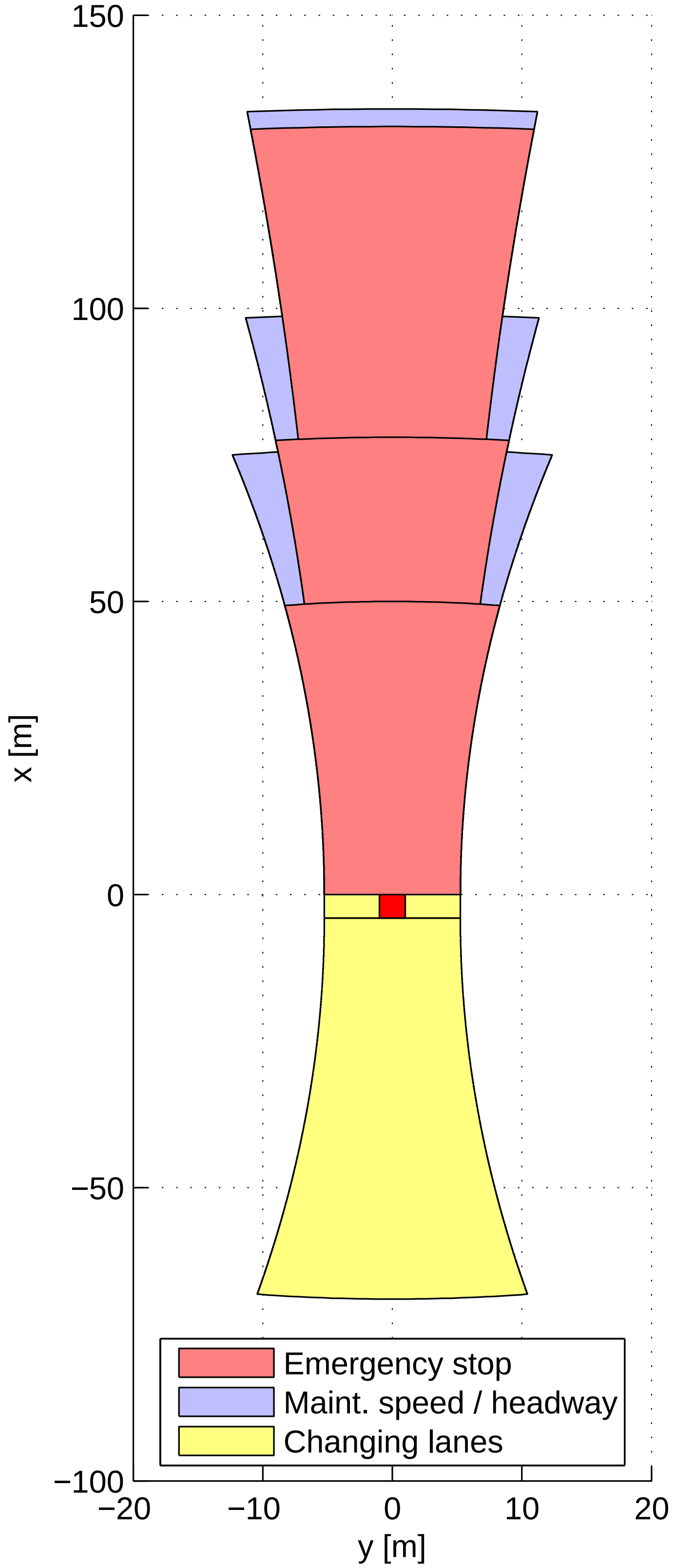


Figure 5.8: Total sensor coverage required for highway driving

In figure 5.8, the red square in the center represents the host vehicle (2 m wide, 4 m long). The jagged shape of the forward-looking detection is caused by the different range requirements for different design speeds.

5.2.2 Metrics

The values presented in the table below represent the most extreme requirements found in the scenarios analyzed in this chapter. A sensor set meeting all these requirements should be able to cover every highway scenario for every highway design speed.

	Range [m]	**Max ang. error [°]**	**Min. ang resolution [°]**
Forward	134	0.14	0.32
Backward	67	0.27	0.64
Lateral	4.55	-	-

One could argue that we have not specificed any requirement on range measurement error so far. The lateral error (see section 4.1.4) caused by range measurement error is very small for radially oriented roads (which is the case for all highway scenarios) except if a nearby vehicle is present on one of the adjacent lanes (see figure 4.7). A value of 0.32 m is sufficient for any angle of θ, and larger values have to be evaluated for the FOV of the specific sensor chosen, using equation 4.8.

Chapter 6

Rural analysis

Rural roads are found outside of the city limits, typically connecting cities to other cities or highways. Intersections and roundabouts are commonly encountered, which require dealing with laterally approaching traffic. In some case a vehicle might be sharing the same lane with opposing traffic. In addition to motor vehicles, vulnerable road users such as pedestrians and cyclists can be encountered, as well as animals (deer, sheep, etc).

Figure 6.1: A rural road (source: Google Streetview)

Road geometry

In order to describe the characteristics of rural roads, we have mainly used the Dutch guidelines provided by the province of Zuid-Holland in the Netherlands [25]. These guidelines mention design speeds of 50, 60 and 80 km/h for rural roads, which will be the speeds used for the calculations in this section. Rural roads have a minimum lane width of 2.70 m, and a minimal width of 3.1 m is used for intersections [25]. In order to simplify things we will assume that all lane in the rural environment are 3.1 m wide.

For the road radii, no information is mentioned in [25], however [17] mentiones the minimum road radii shown in table 6.1. Even though the document is old, the values defined in it are calculations based on friction and superelevation of the road surface, which we assume are still valid today. Superelevation (also known as cant) is the difference in height between the two sides of the road, and a higher value of superelevation increases the lateral friction and therefore allows for a smaller road radius. Table 6.1 shows the values for 5% superelevation, which is maximum for rural roads [17].

Design velocity [km/h]	Minimum curve radius [m]
80	260
60	130
50	85

Table 6.1: Minimal curve radius versus design speed for rural roads, concidering 5% superelevation

We will use the values presented in table 6.1 for several calculations in this chapter. Just like the highway scenario, we will again assume circular sections of road, which are the most challenging in terms of curvature and required detection coverage.

Road users

We can expect pedestrians and cyclists on rural roads, however different guidelines are defined for different design speeds. On 50 km/h and 60 km/h roads cyclists and pedestrians are sometimes allowed to share the road with motor vehicles, however 80 km/h roads require separate cycling lanes [78] [25] [17]. Furthermore, bicyclists do not get priority on rural roundabouts and intersections [25]. Animals however obviously do not obey these rules, and can be encountered on all rural roads.

Lateral spacing

We have to select a value for the minimum lateral separation that we can expect between two vehicles driving next to eachother, which is essential for angular resolution calculations. The reasoning is the same as for the highway environment (see section 5). A value of 0.65 m of lateral spacing has been selected using figure 6.2 found in [40].

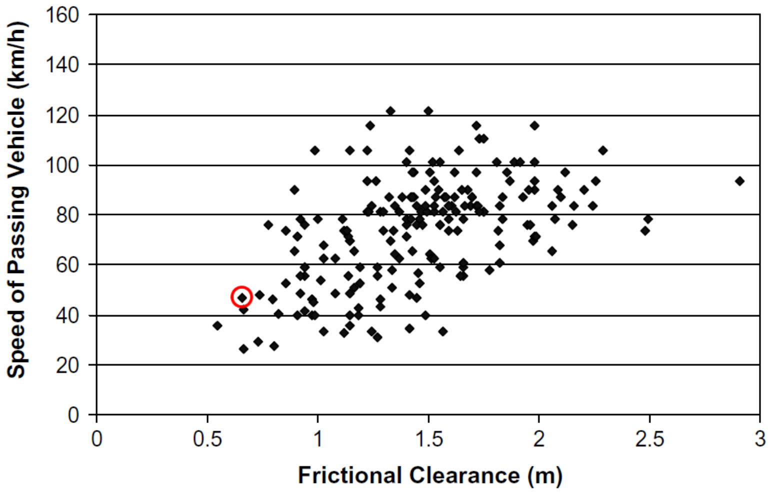


Figure 6.2: Lateral distance between two vehicles (named Frictional Clearance) at different vehicle speeds. The red circle indicates our chosen value (source: [40])

Deceleration, safety and comfort

Just like we did for the highway analysis, we will use a deceleration of 5 m/s^2 to calculate required braking distances in case of an emergency stop. A deceleration of 2 m/s^2 will be used in situation where confortable braking is desired. In some of the calculations a human reaction time must be taken into account. We have selected a human reaction time of 1 s, which is described as as 'reasonably quick' in [76]. In other cases, zero reaction time is assumed.

6.1 Scenarios

Based on earlier research [47, 62, 9], the following scenarios were identified to be typical to rural driving:

1. Emergency stop
2. Maintaining speed / headway
3. Changing lanes
4. Overtaking against direction of traffic
5. Lane sharing
6. Turning at an intersection
7. Crossing an intersection
8. Roundabouts

6.1.1 Emergency stop

Figure 6.3: Example of an animal blocking the road

If a stationary or slow-moving object is present on the road, an emergency stop might me necessary in order to prevent a collision with this objects. In addition to the detection of vehicles and other (stationary) objects, the host vehicle must be able to reliably detect pedestrians, cyclists, and also animals which may unexpectedly enter the road (see figure 6.3). Their movements have to be analyzed and predicted. Pedestrians might be walking in the road shoulder, but could also be crossing the road. Cycling lanes, as shown on figure 6.1, might be occupied by cyclists, which could prevent opposing traffic from passing eachother. All of these situations might require an emergency stop to be carried out.

Metrics (vehicles / motorcycles)

Different design speeds result in different breaking distances, and in turn different requirements on accuracy and resolution. The calculations used are described in detail in section 4.1. The following values were calculated:

Design speed [km/h]	Range [m]	Max ang. error [°]	Min ang. resolution [°]
80	50	0.37	0.74
60	28	0.65	1.33
50	20	0.92	1.86

Table 6.2: Required values for the forward-looking sensing for the 'emergency stop' scenario

Metrics (pedestrians / cyclists / animals)

In [25] it is mentioned that roads without a separate bicycle lane (such as shown in figure 6.1) can have a maximum speed of just 60 km/h. Therefore we will assume that we will not encounter pedestrians or cyclists on roads with a design speed above 60 km/h. Using the error values defined in table 4.1 in section 4.1.4, we can calculate the maximum acceptable error for the detection of vehicles and pedestrians. Again, the calculations used are described in detail in section 4.1. The following tables show the values calculated for pedestrian, cyclist and animal detection:

Design speed [km/h]	Range [m]	Max ang. error [°]	Min ang. resolution [°]
60	28	0.26	-
50	20	0.36	-

Table 6.3: Required values for pedestrian detection for the forward-looking sensing for the 'emergency stop' scenario

Design speed [km/h]	Range [m]	Max ang. error [°]	Min ang. resolution [°]
60	28	0.46	-
50	20	0.64	-

Table 6.4: Required values for cyclist detection for the forward-looking sensing for the 'emergency stop' scenario

In addition, we have to deal with the potential threat of animals on the road. Obviously animals come in different sizes, and the larger the animal, the more dangerious its going to be to the passengers. According to [45], deer are the main animals that cause (potentially fatal) crashes, as well as several larger animals such as elk and moose (which don't live in the Netherlands). For animals smaller than deer, we will assume that they're not a threat to the safety of the passengers of the host vehicle. Lets assume that a deer is at least 0.5 m wide no matter what direction we're looking from. If we assume that we want to detect animals that are 0.5 m wide or larger, we can calculate the following values:

Design speed [km/h]	Range [m]	Max ang. error [°]	Min ang. resolution [°]
80	50	0.29	-
60	28	0.51	-
50	20	0.72	-

Table 6.5: Required values for animal detection for the forward-looking sensing for the 'emergency stop' scenario

The tables above do not contain any numbers for the required angular resolution. Virtually all existing pedestrian / animal / cyclist recognition systems rely on image processing for the recognition process, for which the performance and the required resolution heavily depend on the processing algorithms used. This makes it very hard to define a required resolution.

Detection coverage

The stationary object that poses the collision threat can either be present on the current lane or on any of the adjacent lanes, or even on multiple lanes. In some cases an emergency stop could be prevented by performing an evasive overtake-like maneuver, while in other cases the vehicle should just break and stay in the current lane. In order to be able to make a decision on this, both adjacent lanes and the current lane have to be covered, as shown in figure 6.4.

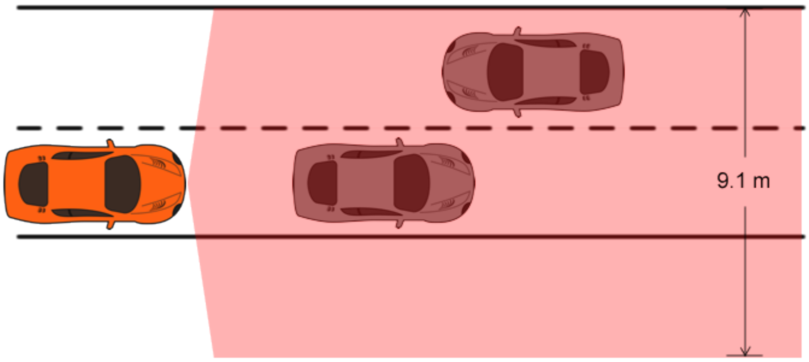


Figure 6.4: Required forward-looking detection coverage for the 'emergency stop' scenario

By applying the same calculations used in 5.2.1 combined with the radii defined in table 6.1, we can plot the exact required detection coverage, which is shown in figure 6.5:

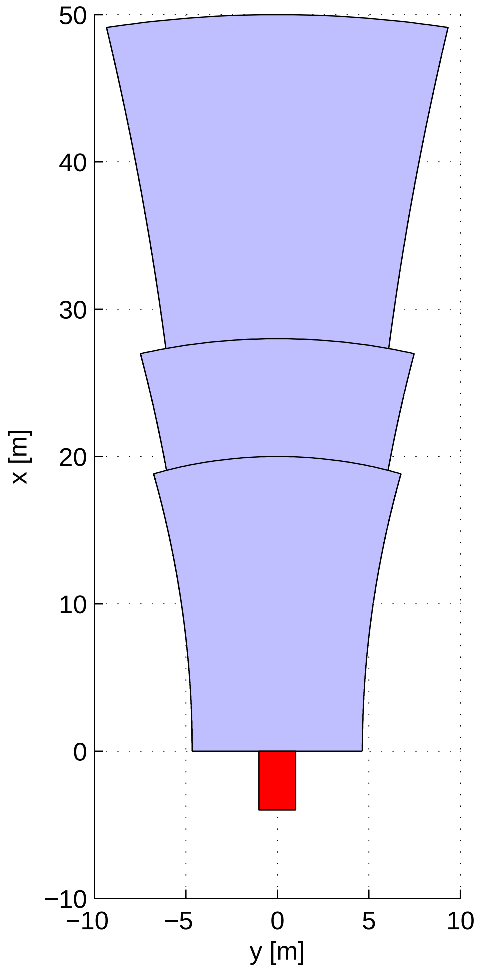


Figure 6.5: Required detection coverage for the 'emergency stop' scenario

6.1.2 Maintaining speed / headway

The host vehicle should be able to maintain a desired fixed speed, while also maintaining a safe headway to the lead vehicle. Headway keeping is a constant control process, and we want this to happen comfortably. Furthermore, we will assume that we do not need to brake for any pedestrians or cyclists in this scenario. As mentioned before, pedestrians and cyclists do not have priority over vehicles in rural areas. The case of braking for pedestrians has been discussed in the 'Lane Sharing' scenario.

Metrics

According to [85], the 90th percentile of relative speed between two adjacent highway lanes is 30 km/h or less, which was based on vehicle measurements. No specific literature was found on relative speeds on rural roads, so we will again assume that no vehicles will have a relative speed larger than 30 km/h, just like we did for the highway environment. The calculations used are described in detail in section 4.1.

Design speed [km/h]	**Range [m]**	**Max ang. error** [°]	**Min ang. resolution** [°]
80	107	0.17	0.34
60	68	0.27	0.55
50	49	0.37	0.76

Table 6.6: Required values for the forward-looking sensing for the 'maintaining speed / headway' scenario

Detection coverage

In order to track the lead vehicle, the system needs detection coverage on the current lane. In order to anticipate on vehicles cutting in, coverage of the adjacent lanes is beneficial. The detection coverage shown in figure 6.4 is sufficient to cover both the current lane and the adjacent lanes. By applying the same calculations used in 5.2.1, combined with the radii defined in table 6.1, we can plot the exact required detection coverage, which is shown in figure 6.6.

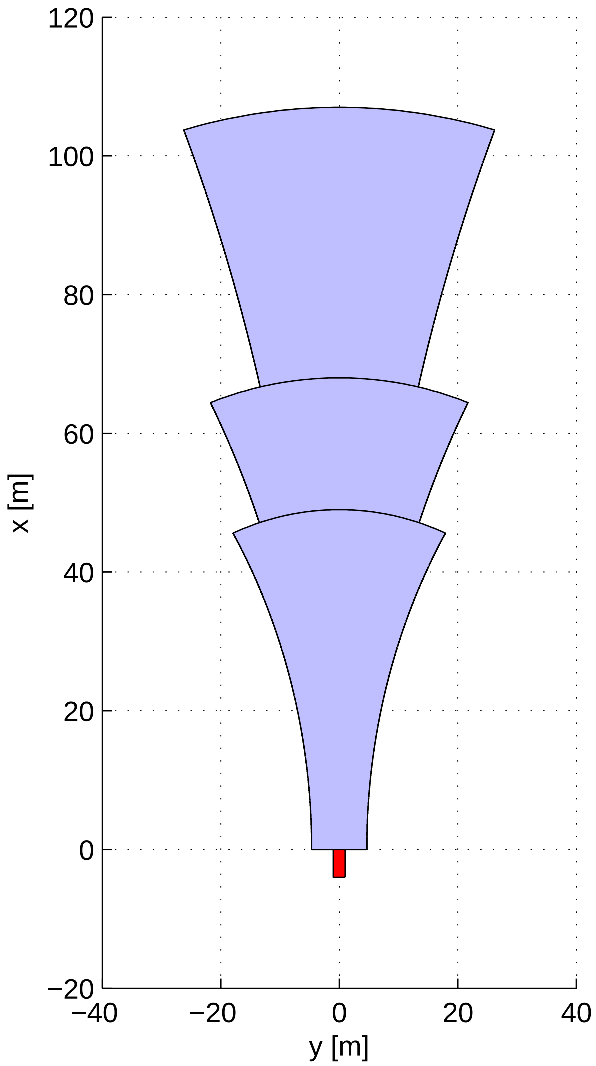


Figure 6.6: Required detection coverage for the 'maintaining speed / headway' scenario

6.1.3 Changing lanes

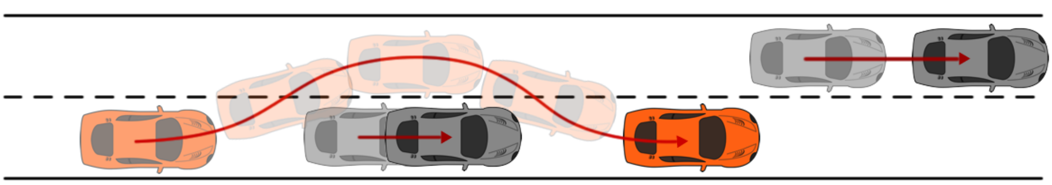


Figure 6.7: A highway-style lane change maneuver

In some cases, two (or more) lanes with the same direction of traffic flow are available for the host vehicle to drive on. This allows the vehicle to change lanes in order to overtake slower lead vehicles. This scenario is essentially the same as the equally named scenario found in the highway chapter (see section 5.1.3), therefore the calculations and reasoning are essentially the same.

Metrics

A lane change maneuver requires different degrees of forward, backward and lateral detection. We will again assume that the forward range is covered by the 'Maintaining speed / headway' and 'Emergency stop' scenarios discussed earlier in this chapter. This leaves only the backward-looking detection. For the backward-looking detection, we will assume that no vehicle will be overtaking the host vehicle with a relative velocity larger than 30 km/h, as discussed in the 'maintaining speed / headway' scenario. The calculations used are described in detail in section 4.1. The following values were calculated:

Design speed [km/h]	Range [m]	Max ang. error [°]	Min ang. resolution [°]
80	67	0.27	0.56
60			
50			

Table 6.7: Required values for the backward-looking sensing

Detection coverage

Like the 'Changing lanes' scenario discussed in the highway chapter, we need backward coverage of both the current lane and the adjacent lanes, as shown in figure 6.8. By applying the same calculations used in 5.2.1, combined with the radii defined in table 6.1, we can plot the exact required detection coverage, which is shown in figure 6.9.

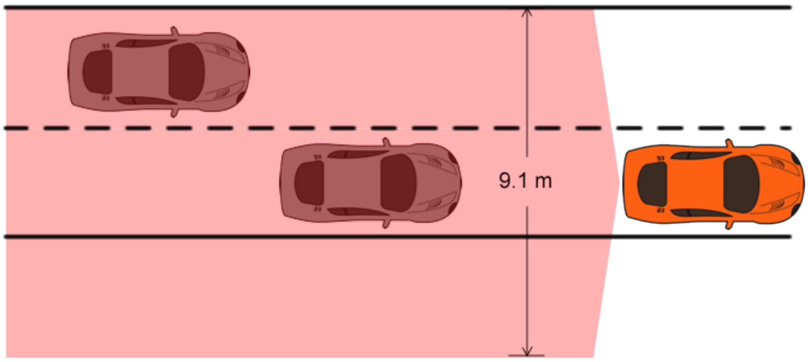


Figure 6.8: Required backward-looking detection coverage for the 'changing lanes' scenario

The lateral detection is also the same as for the 'Changing lanes' highway scenario, see section 5.1.3 for a more detailed explanation. The only difference is the lane width, which means a slightly narrower coverage area is required.

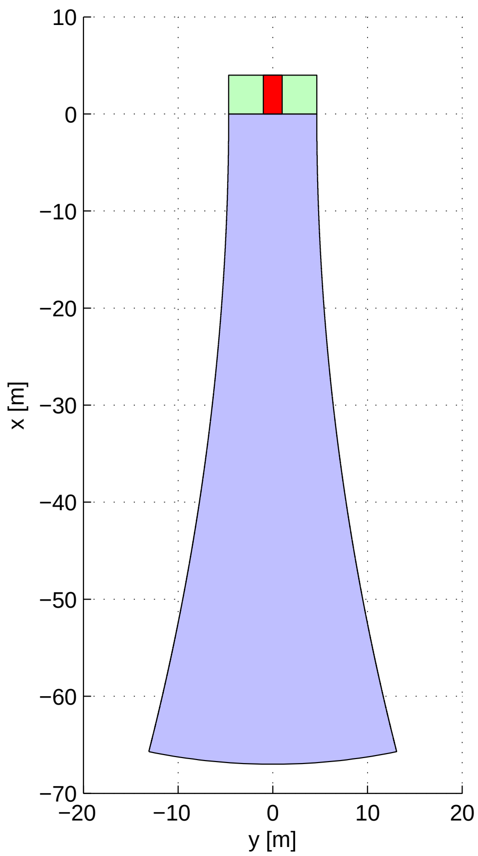


Figure 6.9: Required detection coverage for the 'changing lanes' scenario

6.1.4 Overtaking against direction of traffic

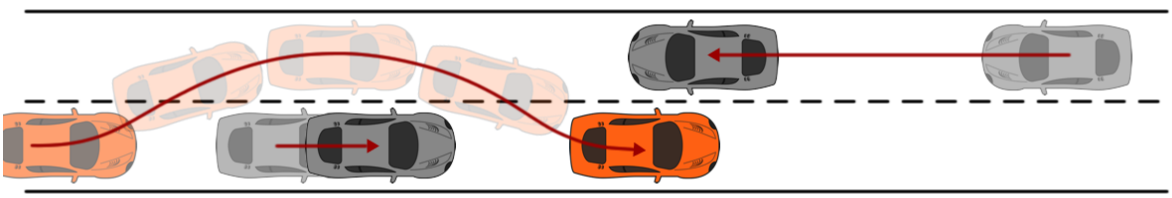


Figure 6.10: An overtaking maneuver which requires going against the direction of travel

The overtaking scenario occurs when the host vehicles wants to pass a slower lead vehicle driving in the same lane. In the 'Highway-like overtaking' scenario, the host vehicle could theoretically take as long as it wants to overtake an other vehicle due to the unidirectional traffic flow. In the case of a two-lane bidirectional rural road however, the host vehicle has to deal with opposing traffic, which puts a limit on the time the host vehicle can spend in the other lane while performing the maneuver. Assuming all traffic obeys the speed limit, we have to deal with relative speeds of up to 160 km/h! The host vehicle should be able to detect the opposing traffic at a distance suffienctly large to guarantee a safe and comfortable overtaking maneuver.

Three overtaking strategies have been identified through observations of human overtaking behaviour [43]:

- **Accelerative**: the host vehicle drives behind the lead vehicle, at the same speed. It waits for a sufficiently large gap w.r.t. opposing traffic, then it accelerates and changes to the opposing lane in order to overtake the lead vehicle.
- **Flying**: the host vehicle does not slow down prior to performing the overtaking maneuver.

- **Piggy backing**: the host vehicle follows a lead vehicle that is also performing an overtaking maneuver at that time.

We concider piggy backing as a dangerous maneuver, since the lead vehicle performing the overtaking maneuver blocks the line-of-sight of the host vehicle, which would prevent it from detecting a any opposing vehicles. The flying strategy can be very effective, but requires a quick (and possibly hazardous) lane change back to the right lane if the maneuver has to be aborted before the slower lead vehicle has been passed. This will probably require braking hard in order to avoid a rear-end collision with the slower lead vehicle. The accelerative is the most safe strategy, and is therefore the only strategy we will concider.

The detection required for the overtaking maneuver consist out of three parts. Forward detection is required to detect opposing vehicles, and to detect the lead vehicle prior to initiating the overtaking maneuver, but we will again assume that the latter has been covered by the 'Emergency Stop' and 'Maintaining speed / headway' scenarios. Backward detection is required to detect vehicles approaching from the back, which could be overtaking the host vehicle right at the moment when it wants to initiate its own overtaking maneuver. Finally, lateral detection is required to make sure no vehicle is present directly next to the host vehicle. The lateral and backward detection discussed in the 'Changing lanes' scenario also apply to overtaking, so we will only focus on forward detection required to detect opposing traffic.

Metrics

The average overtaking maneuver on a rural road takes 7.55 - 7.8 seconds [43] [29]. Lets say our overtaking maneuver can be completed in 7.6 s. According to [30], both Israeli design standards and the American AASHTO recommend a 3 s safety margin after the completion of the overtaking maneuver. Not implementing would result in virtually zero residual distance between the vehicles after the completion of the overtaking maneuver, which would not only scare drivers and passengers of the host vehicle, but also leaves no room for error. Concidering this 3 s margin and an overtaking maneuver duration of 7.6 s, we can calculate the following values:

Design speed [km/h]	**Range [m]**	**Max ang. error** [°]	**Min ang. resolution** [°]
80	467	0.04	0.08
60	350	0.05	0.11
50	292	0.06	0.13

Table 6.8: Required values for the forward-looking sensing for the 'overtaking against direction of traffic' scenario

In [17], a sight distance of 350 m is defined for an overtaking scenario where opposition vehicles are both travelling at 60 km/h, which is in accordance with our calculations.

Detection coverage

The opposing vehicle will be in both the adjacent lane and in the same lane as the host vehicle during portions of the overtaking maneuver. The required detection coverage is shown in figure 6.11. It should be noted that the rightmost lane in the lower half of figure 6.11 should also be covered in order to merge back into the original lane, but this coverage is discussed for the 'Changing lanes' scenario.

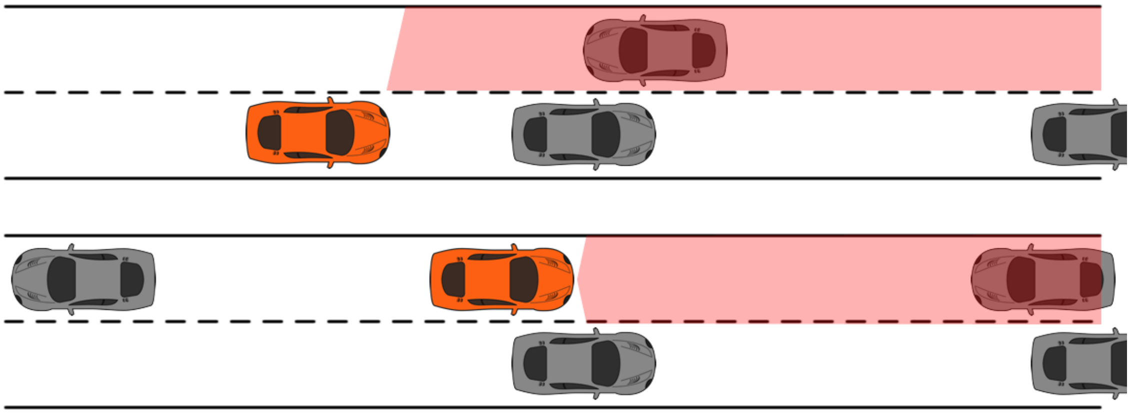


Figure 6.11: Coverage required prior to (above) and during the maneuver (below)

The calculations used in 5.2.1 along with the radii defined in table 6.1 result in strange shapes due to the extremely large ranges required. An example for the 80 km/h case is shown in figure 6.12. The 50 and 60 km/h cases could not be plotted using the calculations used in 5.2.1 due to singularities.

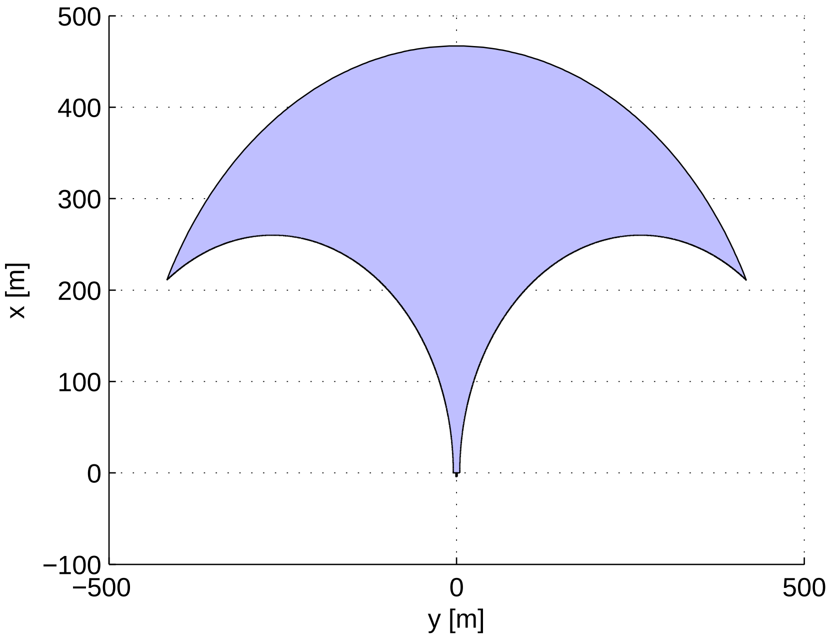


Figure 6.12: Strange coverage pattern calculated for 80 km/h, for the 'overtaking against direction of traffic' scenario

6.1.5 Lane sharing

Figure 6.13: A shared-lane road, with passing zone on the left

Sometimes a single lane has to be used by vehicles traveling in both directions. This lane is usually just wide enough to allow vehicles to pass eachother at a low speed, and it might require one or both vehicles to partially drive into the road shoulder. Some roads have passing zones, a small widened section of road that facilitated the passing of two opposing vehicles (see figure 6.13). These roads can have a design speed of up to 60 km/h [25]. Pedestrians and cyclists commonly share the road with motor vehicles.

Metrics (vehicles / motorcyclists)

We are dealing with an opposing vehicle that has to perform the same braking maneuver, and this opposing vehicle is likely to be operated by a human driver, hence we need to his or her reaction time into account. We will use a 1 s reaction time as defined by [76]. The calculations used are described in detail in section 4.1. The following values were calculated:

Design speed [km/h]	**Stopping distance [m]**		
	Normal	**Incl. reaction time**	**Total**
60	70	86	156
50	62	49	111

Since we're dealing with a single lane and a single opposing vehicle we don't have to worry about the sensor's ability to separate vehicle or detecting in which lane it is, hence the angular resolution and maximum error are irrelevant in this case.

Metrics (pedestrians / cyclists)

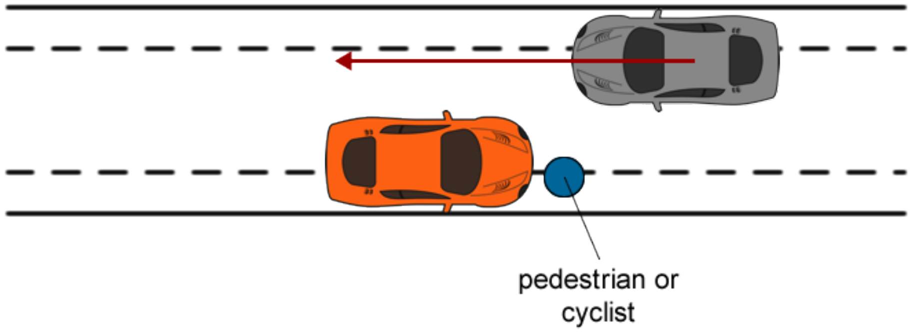


Figure 6.14: Scenario that requires braking for a pedestrian or cyclist

For this scenario we also have to deal with pedestrians and cyclists. Figure 6.14 shows a situation where a pedestrian or cyclist is standing still on the side of the road. The host vehicle can't pass the cyclist because an oncoming car is about to occupy the other side of the road, hence it needs to detect the pedestrian / cyclist and act adequately. The host vehicle should at least be able to perform an emergency stop maneuver in order to not hit the pedestrian / cyclist, which means that the required values are equal to the ones found for the 'emergency stop' scenario in section 6.1.1 (see tables 6.4 and 6.3).

Detection coverage

We need forward detection in order to detect the oncoming vehicle in time. In [25] a maximum road width of 5.70 m is defined for roads like one discussed in this scenario. The host vehicle will mainly be driving in the middle, however it has to move over to the right side of the road when opposing traffic is detected. If the host vehicle want to pass a cyclist (or 2 cycling alongside of eachother, which is legal in the Netherlands), it has to move over all the way to the left side of the road. Therefore the host vehicle has to be able to fully cover the entire road surface. If we assume that the host vehicle is at least 1.4 m wide (as done in [2]), we would need a 5 m wide strip of detection coverage on either side of the vehicle, as illustrated in figure 6.15.

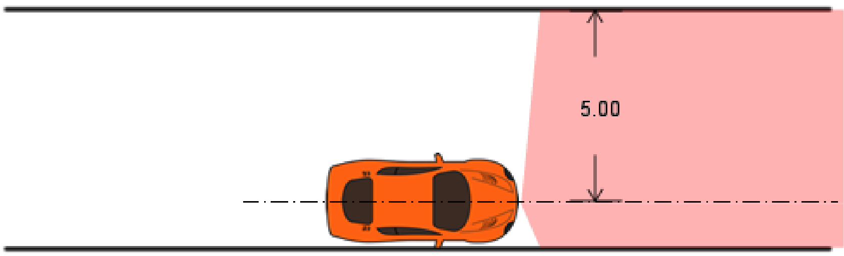


Figure 6.15: Forward detection coverage for the 'lane sharing' scenario

The host vehicle also needs to detect the presence of any cyclists, pedestrians or vehicles immediately next to itself so it can safely pass these. The lateral detection illustrated in figure 6.16 should be sufficient (again calculated for a vehicle width of 1.4 m). Again, since the host vehicle can be on either side of the road, we will need this coverage on both sides of the vehicle.

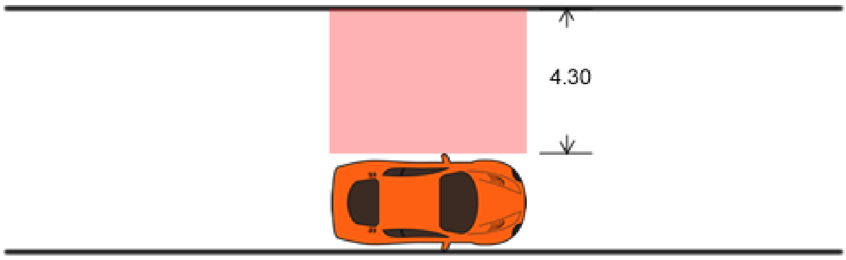


Figure 6.16: Lateral detection coverage for the 'lane sharing' scenario

By applying the same calculations used in 5.2.1, combined with the radii defined in table 6.1, we can plot the exact required detection coverage, which is shown in figure 6.17.

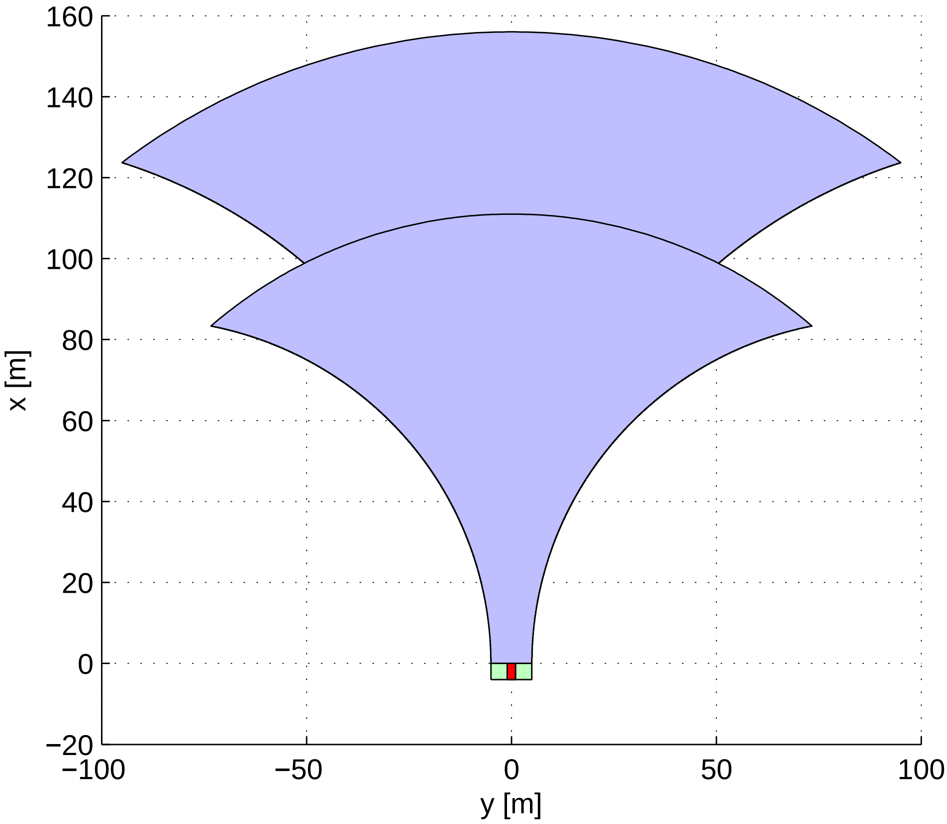


Figure 6.17: Required detection coverage for the 'lane sharing' scenario

6.1.6 Turning at an intersection

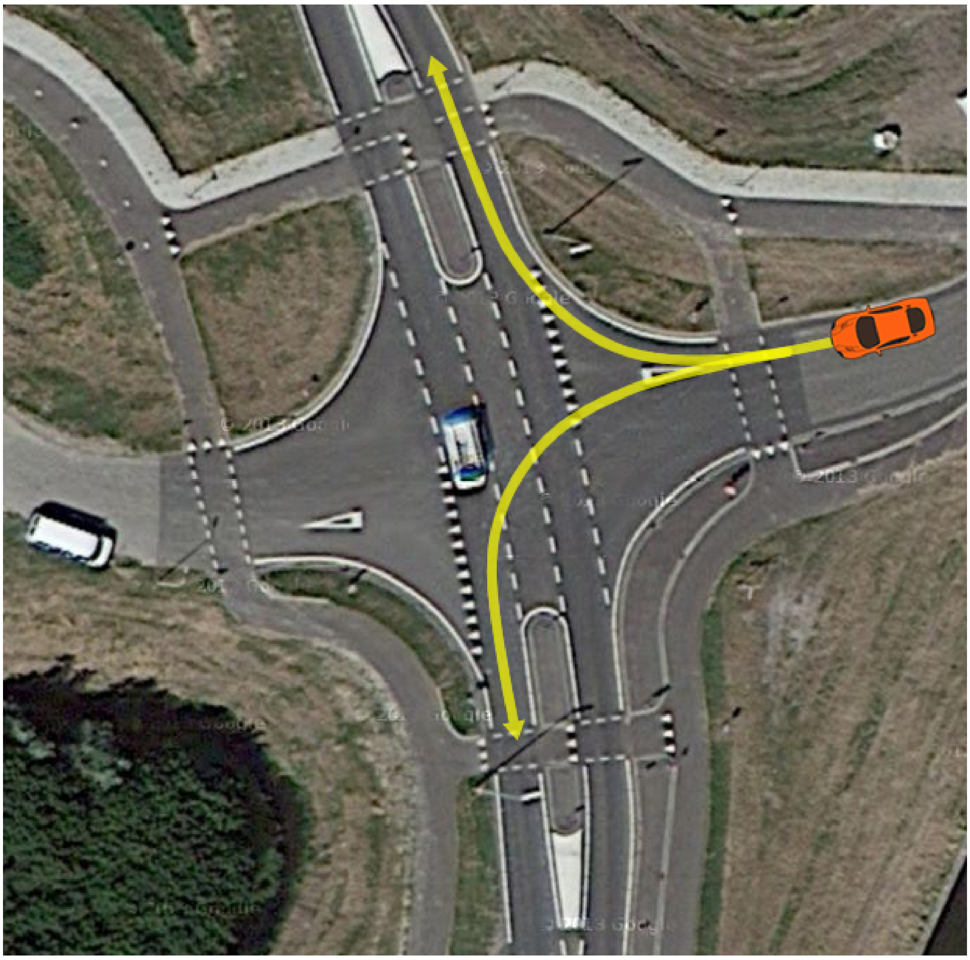


Figure 6.18: Examples of a right and left-hand turn at a typical rural intersection (source: Google Maps)

The intersection shown in figure 6.18 shows two intersecting roads, where one road has priority over the other, as indicated by the 'shark teeth', the triangular marks on the road surface. In literature, the road having priority is commonly called the major road, and the other road is simply called the minor road. For convenience, we will also use these terms. If a vehicle on the minor road wants to merge with major road traffic coming from the left or right, traffic should be sufficiently far away to allow the minor road vehicle to merge into (or cross) the major road stream. A commonly used measure is the time gap, which is the time it takes the major road vehicle to reach the conflict zone of the intersection after the arrival of the minor road vehicle [14]. In the literature, the minimum value of this time gap that a minor road driver is willing to accept is called the critical gap. Since we would like an automated vehicle to behave similar to human drivers, we will use the average critical gap as a measure to calculate the sensing requirements.

In [25] it is mentioned that pedestrians and cyclists should not have priority at rural intersections, and bicycle lanes should be diverted away from the intersection. We will therefore assume that we don't have to deal with pedestrians or cyclists for this scenario.

Metrics

Many studies have been performed on the gap acceptance of human drivers. In [41], a critical gap size of 7.5 s was discovered, and was found to be independent of the speed of the approaching vehicle. However, other work has shown that the velocity of the approaching vehicle was the variable that had the largest effect on the critical gap size [4], which corresponds to other previous studies according to [91]. In [91], critical gaps of 5.82 s and 7.44 s were found for major road traffic approaching at 88.5 km/h and 40.2 km/h respectively, for a two-lane rural road with traffic driving in opposite directions. We've used linear interpolation to determine the gap values for 50 60 and 80 km/h:

Design speed [km/h]	**GAP [s]**
88.5	5.82
80	6.105
60	6.78
50	7.11
40.2	7.44

The interpolated gap values were used to derive the required detection range. The calculations used are described in detail in section 4.1. The following values were calculated:

Design speed [km/h]	**Range [m]**	**Max ang. error [°]**	**Min ang. resolution [°]**
80	136	0.13	0.27
60	113	0.16	0.33
50	99	0.19	0.38

Table 6.9: Required values for the lateral sensing for the 'turning at an intersection' scenario

[17] has also defined lateral sight distances at rural intersections, which are shown in table 6.10. The values don't differ more than 20 % from our calculated values.

Design speed [km/h]	**Sight distance [m]**
50	80
60	100
80	150

Table 6.10: Lateral intersection sight distances as defined by [17] (translated from Dutch)

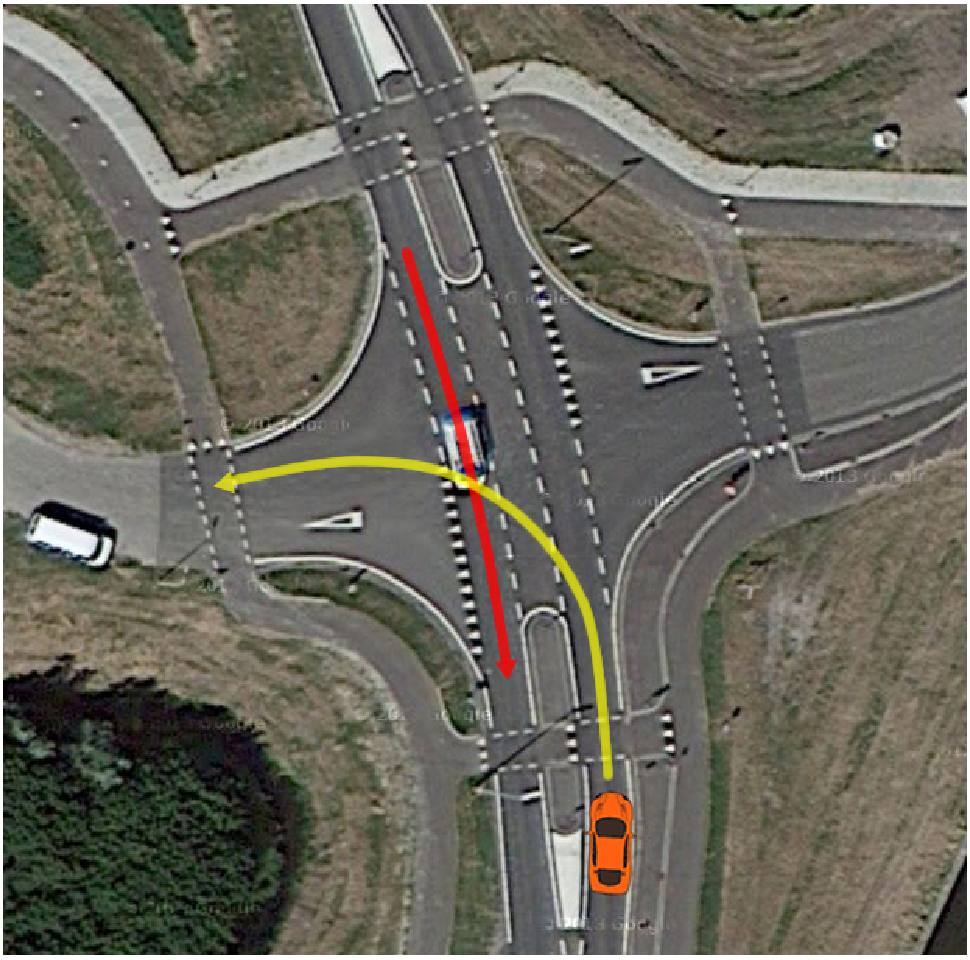


Figure 6.19: Left-hand turn path interfering with a crossing vehicle's path (source: Google Maps)

Figure 6.19 shows a different situation where the host vehicle is on the major road and wants to perform a left-hand turn onto the minor road. Traffic traveling in the opposite direction has priority in this case, and could obstruct the host vehicle's turning maneuver. A safe time gap w.r.t. the opposing vehicle is required. In the literature, a critical time gap of 4.1 s was found for such a maneuver [41]. Unfortunately no other documents were found to compare this value or to verify that is independent of the design speed. The calculations used are described in detail in section 4.1. The following values were calculated:

Design speed [km/h]	**Range [m]**	**Max ang. error [°]**	**Min ang. resolution [°]**
80	92	0.20	0.40
60	69	0.27	0.54
50	57	0.32	0.65

Table 6.11: Required values for the forward-looking sensing for the 'turning at an intersection' scenario

Detection coverage

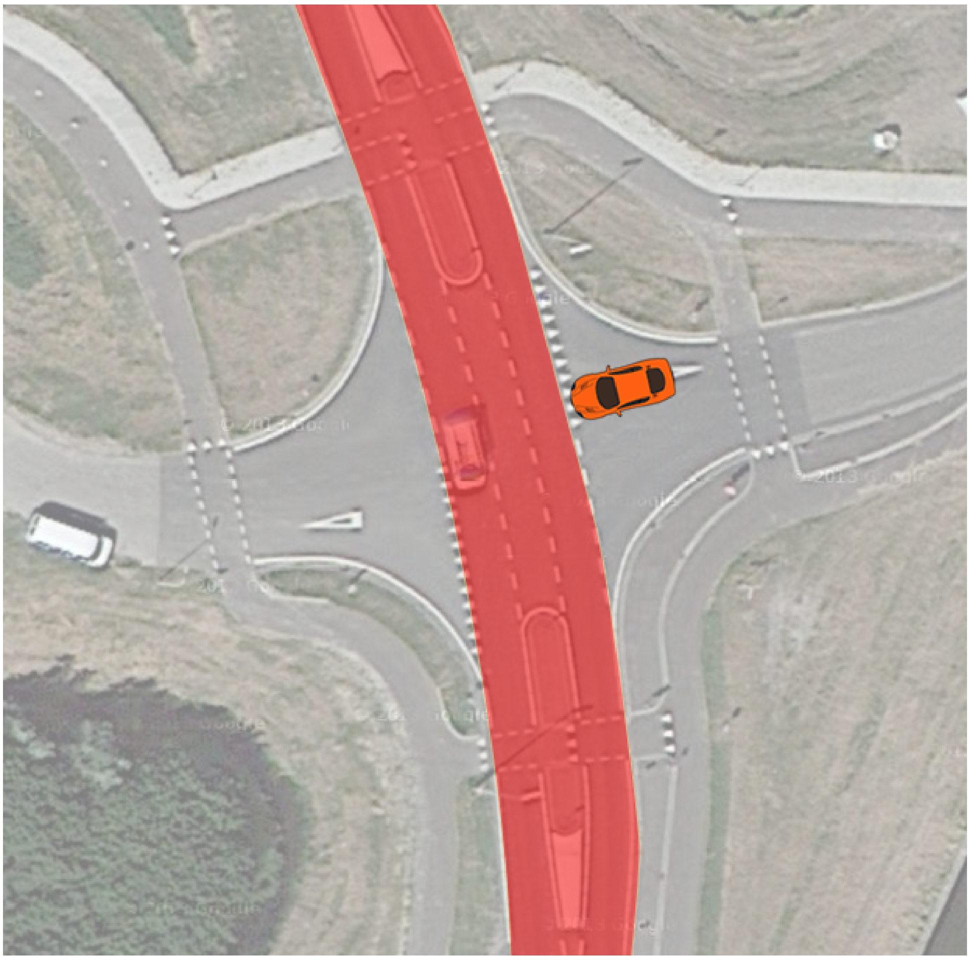


Figure 6.20: Lateral detection coverage required for the 'turning at an intersection' scenario

Figure 6.20 shows the required detection coverage for the intersection discussed for this scenario. Both sides have to be covered in order to detect traffic from both sides. If we assume that we do not have to cover more than a width of 3 lanes (1 lane for each direction and a median in the middle). We assume that if there are more lanes to cross, there will be a median large enough for the vehicle to wait, effectively cutting the turning maneuver in half. According to [25], the lane width at a rural intersection must be 3.1 m, therefore we require the width of the red area (see figure 6.20) to be 9.3 m wide.

Figure 6.21: Forward detection coverage required for the 'turning at an intersection' scenario

For the situation shown in figure 6.21 we need to detect vehicles on just the opposite lane(s). If we assume the host vehicle never has to cross more than two lanes at the same time in this situation, we need the red section to be 6.2 m wide (again concidering a 3.1 m lane width). For symmetry reasons, we will assume that we need this coverage on both sides of the vehicle. This means we need a total coverage width of five lanes: the two lanes to the left, two on the right, and we'll simply fill in the gap between the two sides to be complete (in other words, we cover the ego lane as well). Maintaining symmetry allows the host vehicle to operate in both left-hand and right-hand driving traffic without having to modify the sensor set. By applying the same calculations used in 5.2.1, combined with the radii defined in table 6.1, we can plot the exact required detection coverage, which is shown in figure 6.22. It should be noted that we have assumed that the intersecting roads form a 90 ° angle, which is recommended by the road construction guidelines [17].

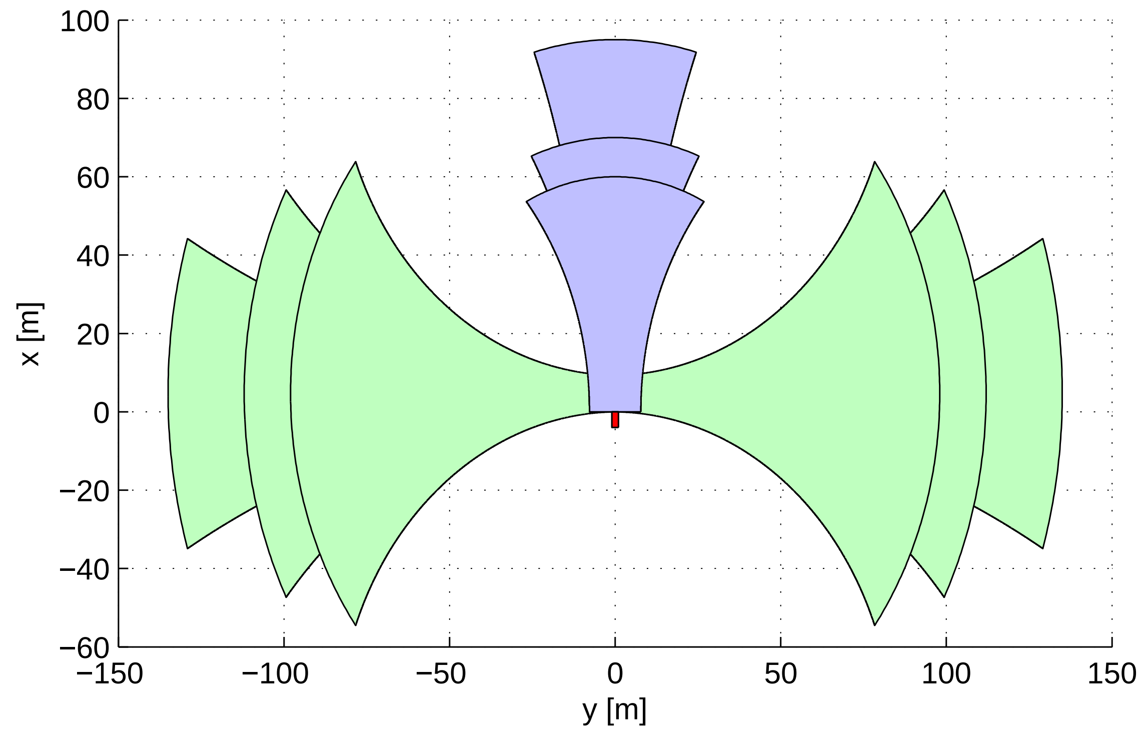


Figure 6.22: Required detection coverage for the 'turning at an intersection' scenario

6.1.7 Crossing an intersection

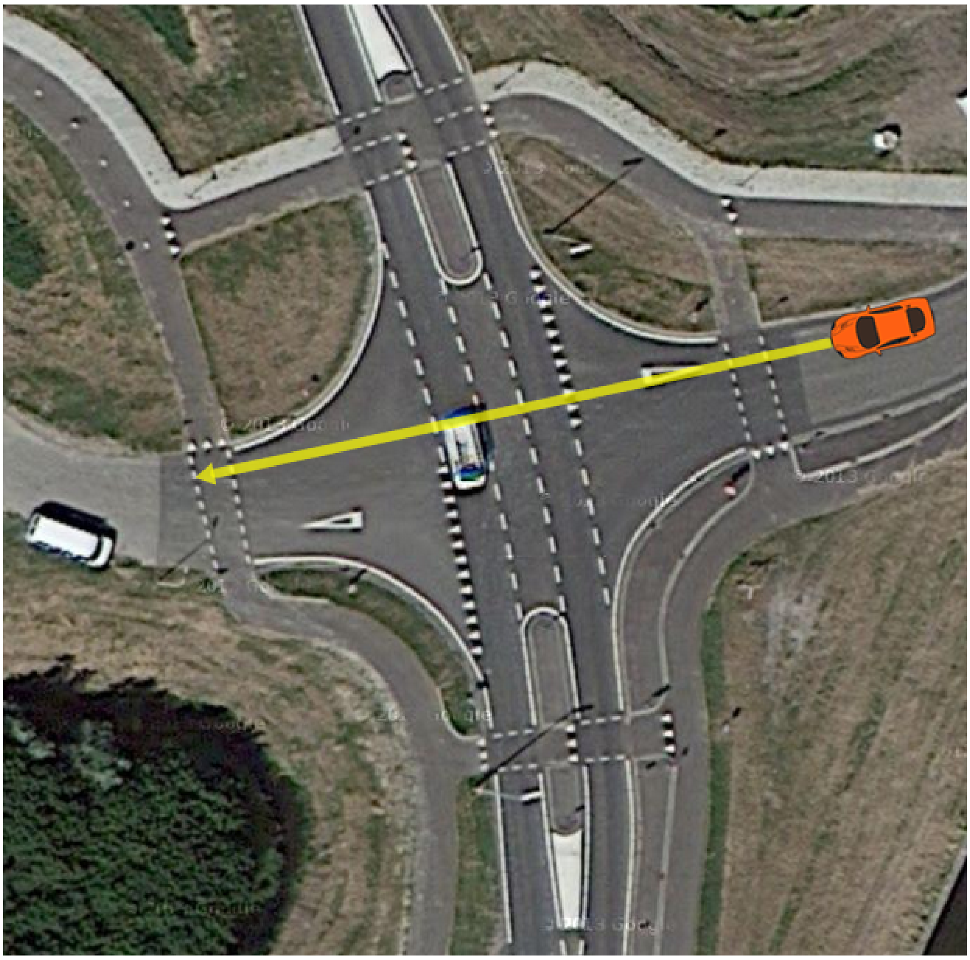


Figure 6.23: Example of a crossing maneuver on a typical rural intersection (source: Google Maps)

When an intersection has to be crossed without traffic light guidance, the host vehicle has to detect vehicles approaching laterally, and should stay clear of these vehicles. We will again assume that we do not have to deal with pedestrians or cyclists since they will not have priority, as was discussed for the 'Turning at an intersection' scenario. For the crossing maneuver, a critical time gap of 6.5 s was defined in [41] for a 2-lane road. If we assume that no more than 3 lanes have to be crossed at once (as discussed for the 'Turning at an intersection' scenario), this translates into the requirements shown in table 6.12. It should be noted that an additional 0.5 s has to be taken into account for each extra lane that has to be crossed [41], therefore we chose a critical time gap of 7 s to calculate these values. The calculations used are described in detail in section 4.1. The following values were calculated:

Design speed [km/h]	**Range [m]**	**Max ang. error [°]**	**Min ang. resolution [°]**
80	156	0.12	0.24
60	117	0.16	0.32
50	98	0.19	0.38

Table 6.12: Required values for the lateral sensing for the 'crossing an intersection' scenario

It should be noted that if the road has a median that is wide enough for the host vehicle to stop on it, then the crossing maneuver can be split in two seperate crossing maneuvers, effectively halving the number of lanes that have to be crossed.

Detection coverage

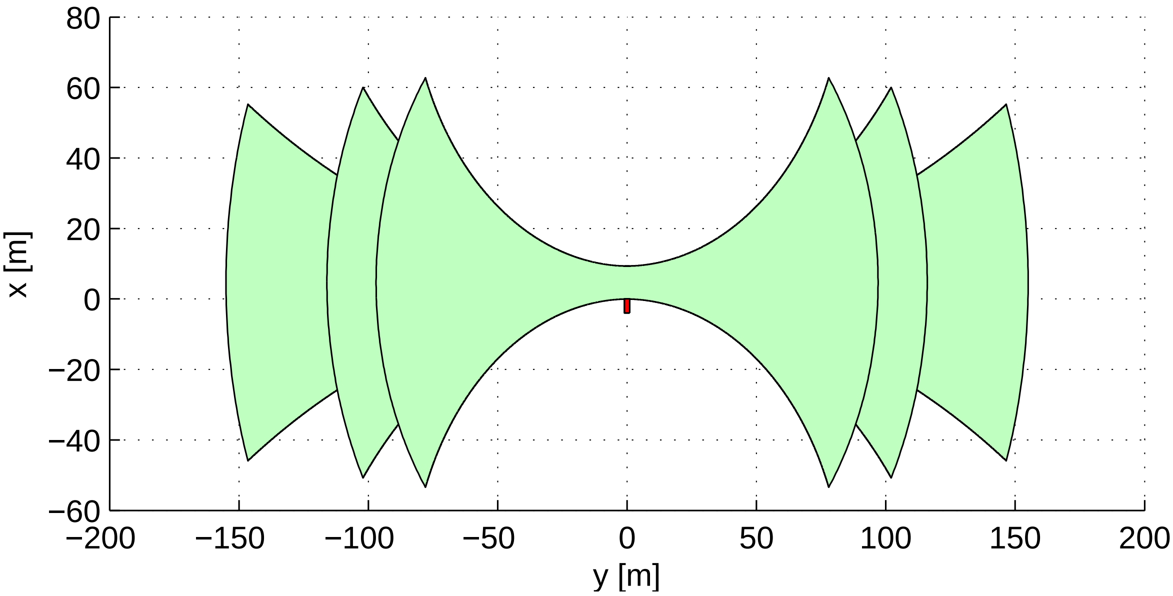


Figure 6.24: Required detection coverage for the 'crossing an intersection' scenario

The detection coverage required for this scenario is roughly the same as the lateral detection coverage proposed in the 'turning at an intersection' scenario (see figure 6.20). By applying the same calculations used in 5.2.1, combined with the radii defined in table 6.1, we can plot the exact required detection coverage, which is shown in figure 6.24. Like the 'Turning at an intersection' scenario, we have assumed that the intersecting roads form a 90 ° angle.

6.1.8 Roundabouts

Figure 6.25: A typical rural roundabout (source: Google Maps)

Roundabouts provide a circular path for all traffic, and allow vehicles to move only in one direction, either clockwise or counter-clockwise depending on the country's traffic rules. Roundabouts are common in Europe and Australia, but are not as widespread in the United States [66]. In the Netherlands, roundabouts are slowly replacing (particular) intersections since they reduce the number of conflict points and therefore enhance safety [77]. Vehicles traveling on the roundabout typically have priority over vehicles that are approaching the roundabout (like the example shown in figure 6.25), but this is not always the case. Roundabouts can have multiple lanes to facility a larger capacity.

Some roundabouts may contain bicycle lanes, as shown in figure 6.25. According to, bicyclists do not have priority over vehicles on the main road in rural areas, thefore we assume that will not have to deal with bicyclists and pedestrians.

Metrics

According to [25] [31], the recommended maximum speed of a vehicle traveling on a roundabout is 35 km/h, and should be no larger than 41 km/h in case of a vehicle making a right turn into the first exit. The roundabout must be designed in such a way that this is achieved. For our calculations, we will assume that traffic on rural roundabout will not travel faster than 41 km/h. In [75] a critical gap of 4-5 s is defined, while [25] [31] both specify a gap of 3.5 s. To be on the safe side, we've decided to select a gap of 4 s. Since roundabouts come with widely varying radii, we will simply use the straight line calculations, which allows us to deal with roundabouts of any radius up to infinity. The calculations used are described in detail in section 4.1. The following values were calculated:

Design speed [km/h]	Range [m]	Max ang. error [°]	Min ang. resolution [°]
80	46	0.40	0.81
60			
50			

Detection coverage

Figure 6.26: Detection required for entering a roundabout (source: Google Maps)

Figure 6.27: Required values for the forward sensing for the 'roundabouts' scenario

The diameter of a roundabout varies greatly. Small roundabouts might be visible using a more narrow area of detection coverage, while a larger rounabout (as shown in figure 6.25) requires a much wider coverage in order to overlook the entire situation. Figures shown in [92] and [75] confirm the need for a wide coverage area. A 180 ° coverage would be ideal, as it would cover every roundabout design assuming that all roads connect to the roundabout in a perpendicular way (which is actually what is recommended by [25]).

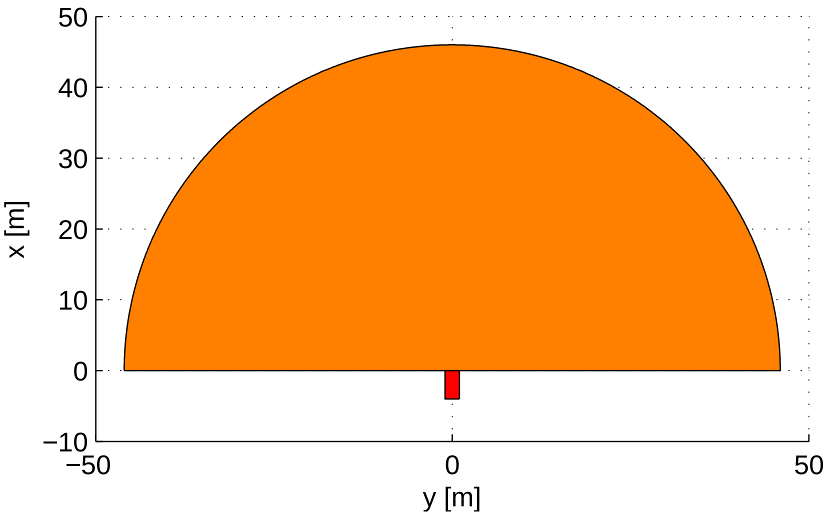


Figure 6.28: Required detection coverage for the 'roundabouts' scenario

Figure 6.28 shows the exact coverage required for this scenario, which is simply a semicircle with a radius of 46 m.

6.2 Requirements summary

6.2.1 Detection coverage

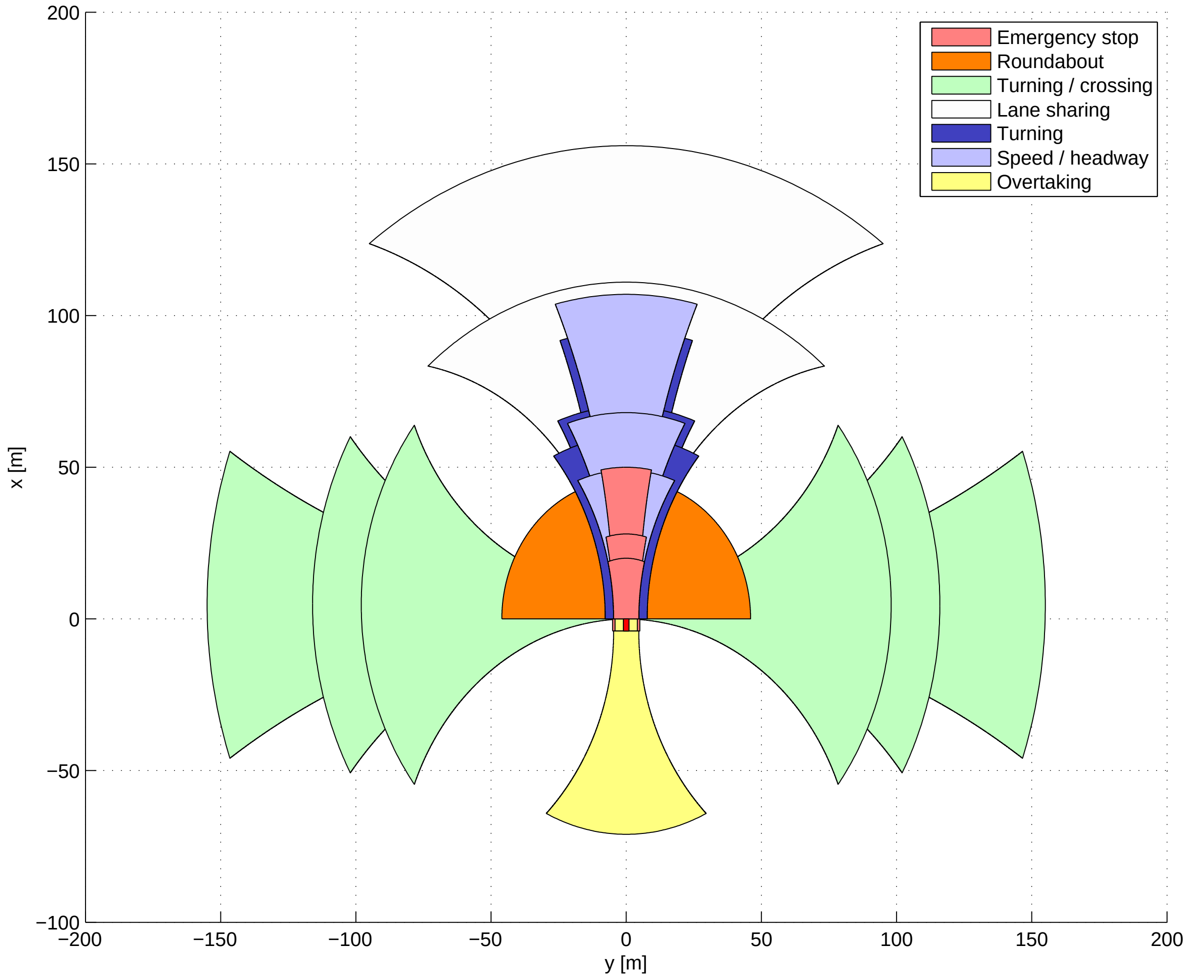


Figure 6.29: Total vehicle detection coverage required for the rural environment

Figure 6.29 shows the required vehcle detection coverage from all scenarios combined. It should be noted that some scenarios were left out since they were totally overlapped by others (i.e. the 'emergency stop' scenario is totally covered by the 'maintaining speed / headway' scenario). The 'Overtaking against direction of traffic' scenario was left out, since currently available sensor technology is simply not able to meet the requirements in terms of range.

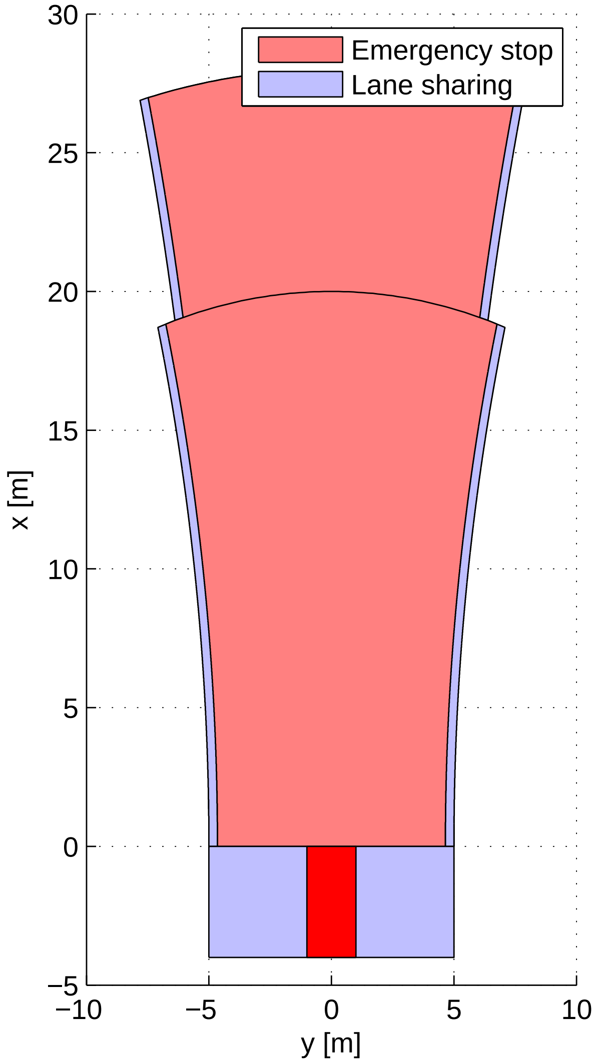


Figure 6.30: Total pedestrian / cyclist detection coverage required for the rural environment

Figure 6.30 shows the required detection coverage for the detection of pedestrians and cyclists. Only the 'emergency stop' and 'lane sharing' scenarios require pedestrian and cyclist detection. Pedestrians and cyclists never have priority on 80 km/h roads, which reduces the required detection distance from 50 m to 28 m. However, 50 m of pedestrian / cyclist would be nice to have, as it would allow for more comfortable braking or an emergency stop on an 80 km/h road should an pedestrian or cyclist break the rules.

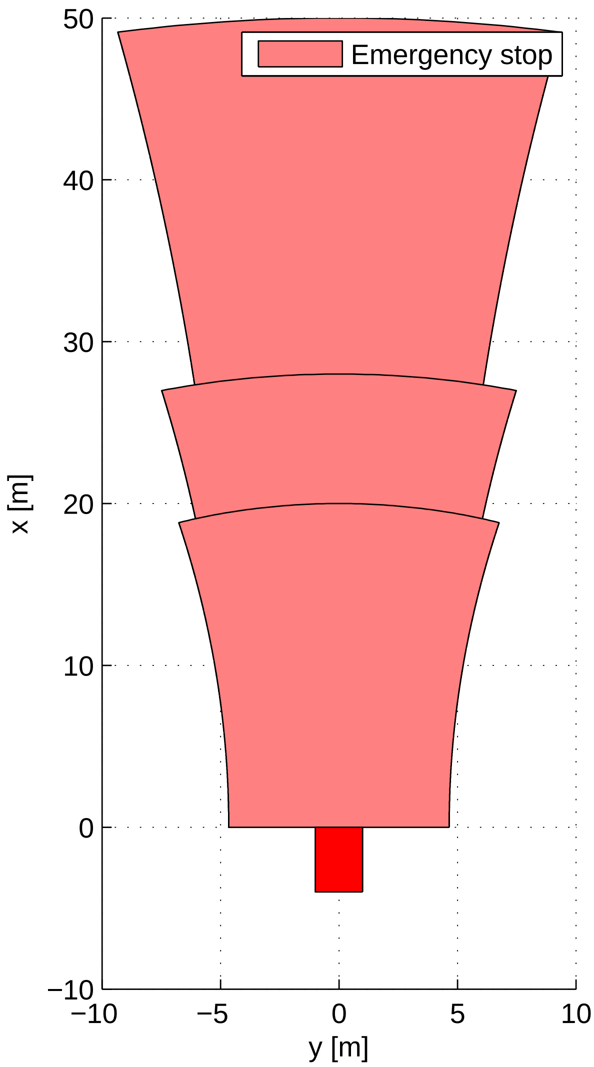


Figure 6.31: Total animal detection coverage required for the rural environment

Figure 6.31 shows the total detection coverage required. Unlike pedestrians and cyclists, animals do not obey traffic rules and can therefore be encountered on 80 km/h as well, which leads to a larger detection range required (50 m).

6.2.2 Metrics

	Range [m]	**Max. ang. err. [°]**	**Min. ang. res. [°]**
Forward	156	0.12	0.24
Backward	67	0.27	0.56
Lateral (long range)	156	0.12	0.24
Lateral (direct)	4.30	-	-
Forward (semi-circular)	46	0.40	0.81

Table 6.13: Vehicle / motorcycle detection requirements for the rural environment

In addition, we require a range resolution of at least 0.32 m since we have to deal with perpendicular roads in several scenarios, i.e. at roundabouts and intersections. This resolution is required for lane estimation purposes, a detailed explanation can be found in section 4.1.4.

We also have to deal with animals, pedestrians and cyclists in some scenarios. In order to be able to perform an emergency stop at an 80 km/h road we need 50 m of animal detection. Since we've assumed that we will not expect pedestrians or cyclists on 80 km/h roads, we only need 30 m of pedestrians / cyclist detection. It should be noted that all these ranges have been calculated concidering an emergency stop, therefore a larger ranger would be beneficial as it allows for more comformtable braking.

	Range [m]	**Max. ang. err. [°]**	**Min. ang. res. [°]**
Forward	28	0.26	-

Table 6.14: Pedestrian detection requirements for the rural environment

	Range [m]	**Max. ang. err. [°]**	**Min. ang. res. [°]**
Forward	28	0.46	-

Table 6.15: Cyclist detection requirements for the rural environment

	Range [m]	**Max. ang. err. [°]**	**Min. ang. res. [°]**
Forward	50	0.29	-

Table 6.16: Animal detection requirements for the rural environment

Chapter 7

Discussion

In this thesis we have investigated and defined sensing requirements for an automated vehicle, for both the highway and rural driving environments. During the literature study that was carried out prior to this thesis, it became apparent that only a little amount of literature was available on this subject. The majority of research in this field is carried out by big automotive compies who keep their information in-house for corporate reasons. This required us to take a from-the-ground-up approach. Different sensor types available for automotive use have been investigated, their characteristics have been described, advantages and disadvantages have been listed, and we have presented a specification list of currently available off-the-shelf units. We have also looked at ADAS systems and other automated vehicle research projects (again with very limited available information) to get a better understanding of what each individual type of sensor is capable of. Methods to determine the required sensor specifications have been derived, some based on literature, while others are new. Driving scenarios have been defined for the highway and rural environment, and sensing requirements have been derived for these scenarios using the methods derived earlier. The feasibility of automation for the highway and rural environments has been evaluated comparing the sensing requirements to the specifications of available sensors. These requirements provide a good starting point for any designer that wants to select a sensor set for an automated vehicle.

7.1 Limitations of this study

The goal of this thesis was to gain insight in the sensing requirements for automated driving in the highway and rural environment. Although the results can be quite useful, there are some significant limitations to this study, which are listed below:

- Literature available on sensing requirements is very limited, this required a from-the-ground-up approach. Because of this, some of the methods used to derive these numbers were a bit simplistic. However we do believe that it provides a good starting point for anyone that has to select a sensor set for an automated vehicle.
- This thesis does not cover any of the control aspects of automated driving. Specific control algorithms might require additional data, and could lead to more demanding requirements. Unfortunately, these are advanced control tasks and are beyond the scope of this thesis and therefore can't be taken into account.
- We have based most calculations on Dutch traffic rules and Dutch road construction guidelines. Although there will be differences compared to other countries, the methods used are generic and easily be adapted for different values.
- We have concidered driving as a 2D problem from a helicopter view perspective. In reality, differences in elevation could become a problem in some cases. Further investigation is required to define requirements on the vertical FOV.
- We have taken a purely theoretical approach. Automated driving is a large and complex problem which has many aspects to it. Simulations could help, but they still provide an idealized environment. Real world testing is required to confirm the sensing requirements found in this thesis. This requires a working vehicle with proper instrumentation, which was unavailable during the writing of this thesis.

- It is assumed that we have perfect knowledge of the ego-vehicle position on the road. Uncertainty about this position and heading will greatly affect in particular the angular accuracy requirements. Possible solution are proposed in section 7.4.
- We have not focussed on detection reliability, except for a brief section on pedestrian recognition. Sensor manufacturers are reluctant in publishing information regarding reliability, which makes it difficult to investigate this sensing aspect.
- We assumed any sensing or processing delays to be zero, however in some cases such delays may have a significant impact on the required sensing range. We will discuss the implications of delays in section 7.4.1.

7.2 Sensor characteristics

Automotive sensors have improved significantly over the last two decades, i.e. the introduction of 77-79 GHz technology has resulted in major improvements of RADAR sensors. When it comes to long-distance sensing, one can choose between RADAR, LIDAR and (night)vision, or a combination of these. Short-range sensing can be achieved (or enhanced) using ultrasonic sensors. We will give a short overview of what these sensors are capable of and what the drawbacks are.

7.2.1 RADAR

RADAR sensors use HF radio waves to detect objects, and are able to do this even in adverse weather or lighting conditions. RADAR sensors can also take advantage of the doppler effect which allows them to directly measure the relative velocity of an object. This allows the sensor to easily distinguish between moving objects and stationary ones. RADAR sensors are widely used in ADAS applications already which makes them quite affordable. The biggest disadvantage of a RADAR is the typically poor angular resolution. This may lead to two objects being perceived as one if these objects are close to eachother while at the same range. However, if the difference in speed between the objects is large enough, the RADAR should be able to differentiate between the objects using the doppler principle. Another problem are ghost targets, non-existing targets created by multiple reflections of the RADAR signal, which are difficult to distinguish from real targets.

7.2.2 LIDAR

LIDAR sensors fire one or more rotating laser beams at a high frequency, and use the time-of-flight principle to measure distances. This allows them, especially the multi-layered units, to capture a high-resolution point cloud of the environment. This information can be used for object detection, as well as mapping an environment (the Google car does this for example). LIDARs can even be used to detect road marking due to their much higher reflectivity compared to the asphalt. LIDARs typically have a very good range and angular resolution. However, the laser beam is affected by weather and lighting conditions. Furthermore, a LIDAR requires at least two returns to identify an object, which means the effective detection range decreases with object size. In terms of cost, LIDARs are generally a lot more expensive than RADAR units. LIDARs also tend to produce large amounts of data, which results in heavy processing needs.

7.2.3 Vision

Vision systems can pick up specific information that other sensors can't pick up. No other sensor is able to read the image on a sign or distinguish a red light from a green one. Vision systems are also able to classify objects, i.o.w. distinguish i.e. between a car, a pedestrian or a tree. Because of this ability they are commonly used for pedestrian / animal / cyclist detection, sign recognition, lane marker detection etc. Stereo camera systems allow depth information to be derived from the image as well, though their accuracy decreaces rapidly as the distance increases. All of this requires heavy processing algorithms to interpret the image (especially stereo systems). The depth interpretation process of the system depends heavily on the processing algorithms, and is only effective up to roughly 40 m. Furthermore, vision systems are heavily affected by lighting and weather conditions.

7.2.4 Ultrasonic

Ultrasonic sensors are simple, affordable and reliable sensors that are able to cover the close up areas around the vehicle. They are typically used for intelligent parking systems on modern cars. LIDAR, RADAR and vision sensors can experience problems with low-range detection due to i.e. line-of-sight (LIDAR, vision) or sidelobing (RADAR) issues. Ultrasonic sensors can compensate for this.

7.3 State-of-the-art sensors, are they good enough?

In chapter 4 we have discussed the different types of sensors available, and we have presented a COTS comparison whenever possible. Are these state-of-the-art sensors good enough to enable reliable autonomous driving? In this section we will discuss this for both the Highway and Rural environment. It should be noted that any FOV/coverage-related issues were left out, these will be discussed separately in section 7.4.2.

Sensor type	**Range [m]**	**Range res. [m]**	**Range acc [m]**	**Ang. res. [°]**	**Ang. acc. [°]**
RADAR	200	2	0.25 or 1.5% >1 m	1	0.1
LIDAR	250	0.04	0.1	0.125	?
Mono vision	-	-	-	0.04*	?
Stereo vision	40	-	0.3	-	?
Ultrasonic	4	?	0.01	-	-

Table 7.1: Specification of best-in-class sensor types

Table 7.1 shows typical specifications of the sensor types discussed earlier. (*) It should be noted that the angular resolution for vision systems was calculated by dividing the horizontal FOV by the horizontal number of pixels. This is purely a theoretical figure since the performance of a vision system depends on its recognition algorithms, not just pixel resolution.

7.3.1 Highway

	Range [m]	**Max ang. error [°]**	**Min. ang resolution [°]**
Forward	134	0.14	0.32
Backward	67	0.27	0.64
Lateral	4.55	-	-

Table 7.2: Highway requirements

Table 7.2 shows the requirements derived for highway driving. From table 7.1 it shows that state-of-the-art RADAR and LIDAR units are able to cover the required ranges and have a sufficiently high angular accuracy. However, the required angular resolution for RADAR sensors tends to be an issue. If a RADAR is used, sensor fusion is required to overcome this drawback. LIDAR sensors don't have this problem, their much higher angular resolution is generally better than what's required. Furthermore, since only low-range "is something present?"-detection is required laterally, ultrasonic sensors could be used to cover these parts if their range is suffiently large enough.

7.3.2 Rural

	Range [m]	**Max. ang. err. [°]**	**Min. ang. res. [°]**
Forward	156	0.12	0.24
Backward	67	0.27	0.56
Lateral (long range)	156	0.12	0.24
Lateral (direct)	4.30	-	-
Forward (semi-circular)	46	0.40	0.81

Table 7.3: Rural requirements (vehicles/motorcycles)

The rural environment requires more extensive sensor coverage, and slightly more demanding angular resolution and angular accuracy. For vehicle and motorcycle detection, the range accuracy and angular accuracy requirements are again within the limits of what LIDAR and RADAR sensors can achieve. Just like for the highway environment, angular resolution is a problem for RADAR sensors, LIDAR sensors are still safely within the limits. There is one major exception: the 'overtaking again direction of traffic' scenario. In this scenario, the host vehicle has to drive on the wrong side of the road in order to overtake a slower lead vehicle, and opposing traffic with relative speeds up to 160 km/h can be expected. This results in very large range requirements (292 m for 50 km/h, and up to 467 m for 80 km/h). None of the available sensors is even remotely able to cover such distances. We therefore have to conclude that this scenario can't be covered using state-of-the-art technology at the time of writing. The numbers displayed in table 7.3 do not include the 'overtaking against direction of traffic' scenario.

In addition to vehicle and motorcyclist detection, the rural environment also requires detection of pedestrians, cyclists and animals. The required metrics are shown in the tables below:

	Range [m]	**Max. ang. err. [°]**	**Min. ang. res. [°]**
Forward	28	0.26	-

Table 7.4: Pedestrian detection requirements for the rural environment

	Range [m]	**Max. ang. err. [°]**	**Min. ang. res. [°]**
Forward	28	0.46	-

Table 7.5: Cyclist detection requirements for the rural environment

	Range [m]	**Max. ang. err. [°]**	**Min. ang. res. [°]**
Forward	50	0.29	-

Table 7.6: Animal detection requirements for the rural environment

Although the ranges and accuracies presented aren't too demanding, detection of these road users can be problematic. Vision systems are used for detection, sometimes accompanied by ranging sensors such as LIDAR or RADAR. A lot of progress has been made during the last few years, and lots of literature about pedestrian detection is available, however current performance levels are unfortunately far from what is required for autonomous vehicles [35][27]. Information on cyclist and animal detection is much more limited, however since both also rely on vision-based recognition methods and are being researched in a much less extensive way, we can expect the same problems.

7.4 Implications of not meeting requirements

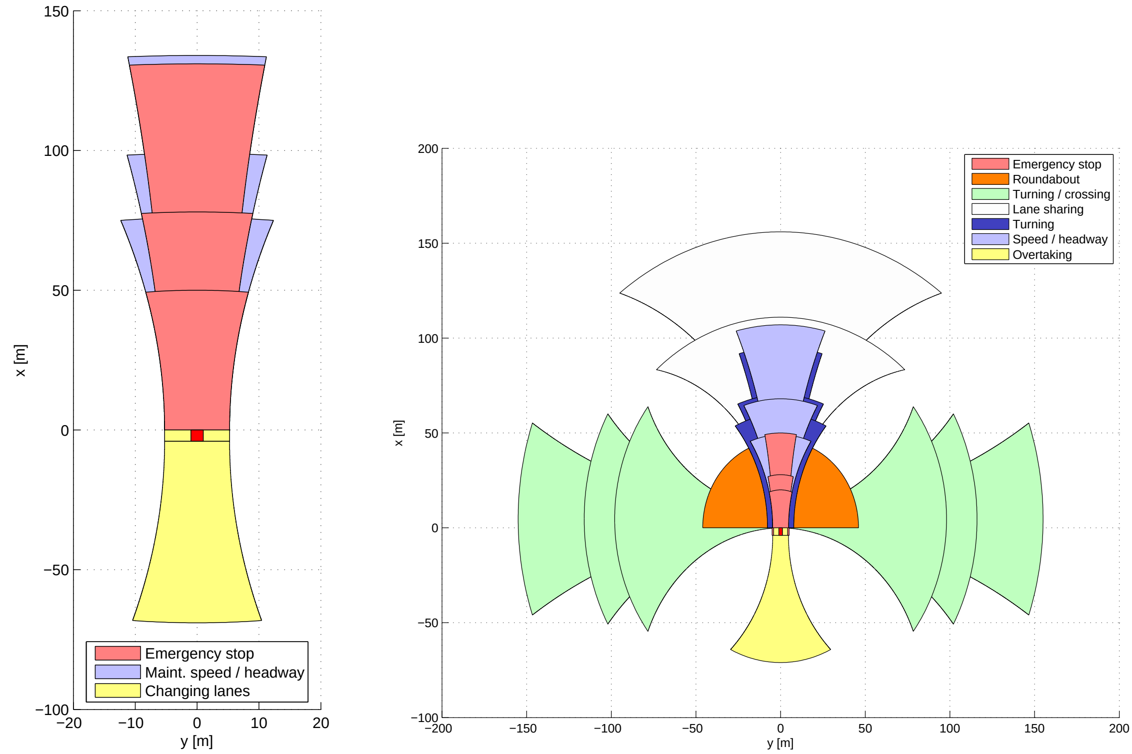
The requirements for some scenarios can be quite demanding, and we have already seen that current technology is not always able to meet them. In this section we will discuss the implications of not being able to meet requirements, and we will discuss possible solutions.

7.4.1 Range

The implication of not meeting the required range is quite simple: the vehicle is unable to detect the other road users in time to guarantee safety or comfort. As a result, the vehicle might not be able to perform a full stop and avoid a collision in an emerency scenario. Another example is a rural intersection, where not having the required range could lead to the execution of a turning or crossing maneuver without properly considering laterally approaching traffic. This in turn could result in other road users having to break hard or, in the worst case, a collision. Range requirements derived for other several scenarios were based around comfort, i.e. the 'maintaining speed / headway' scenarios for both the highway and rural environments. Lacking the required range would require braking outside of the limits of comfort, which could be uncomfortable for the passengers of the vehicle. However, since there's no direct safety aspect involved, one can decide to sacrifice a little comfort to enable the system to cover some additional scenarios.

As mentioned earlier, we have assumed the effects of sensor/processing delays to be zero. In some cases however, these delays may have a significant impact on the required sensing range. Although we have neglected these delays in our calculations, they can easily be incorporated in the equations. For the calculation of ranges based on stopping distances, equation 4.3 contains the reaction time term t_{react}. This term was used to incorporate human reaction time, but it can also be used to correct for any delays. For scenarios where TTC is used to derive the range, one can simply add the amount of sensor delay to the TTC value τ in equation 4.5. Whether or not a certain amount of delay will actually be an issue depends on the vehicle speeds and of course the size of the delay, and has to be evaluated for each scenario.

7.4.2 Detection coverage



(a) Highway **(b)** Rural

Figure 7.1: Required coverage for the Highway and Rural environment

Figure 7.1 shows the required detection coverage for the highway and rural environment. While the highway environment mainly requires forward and backward detection coverage, the rural environment has turned out to be more of a challenge when it comes to meeting detection coverage needs. Covering all of this could lead to the addition of a large number of sensors, depending on which type and model of sensor is chosen. However, by picking a sensor set that is able to cover the most important parts of the required coverage, we enable the vehicle to drive in the majority of scenarios without any problems. Lets look at the example of sharing a lane, as described in section 6.1.5. Technically speaking, we could expect this road to have the rural road curvature values described in table 6.1. However, no strict guidelines were found on what the curvature of such a road can be, which lets us to believe that the designer has to rely on some common sense when designing such a road. One may expect this road to be fairly straight in most cases, which would make it easy for the driver to spot oncoming road users in time. By simply covering just a center portion of the coverage determined for this scenario (see figure 6.17), we should already be able to cover a large portion of such roads. If the available coverage of a chosen sensor set is not sufficient to cover a specific road, control should simply be handed back to the driver. Similar reasoning can be used for rural intersections. One may expect the majority of rural intersections to be fairly straight, with some exceptional cases every now and then. Figure 7.2 shows an example of limited coverage. Here, it was assumed that roads approaching an intersection are fairly straight, and were therefore plotted with a minimal radius of 500 m. The result is a detection coverage overview that is easier to achieve using (potentially) a smaller number of sensors.

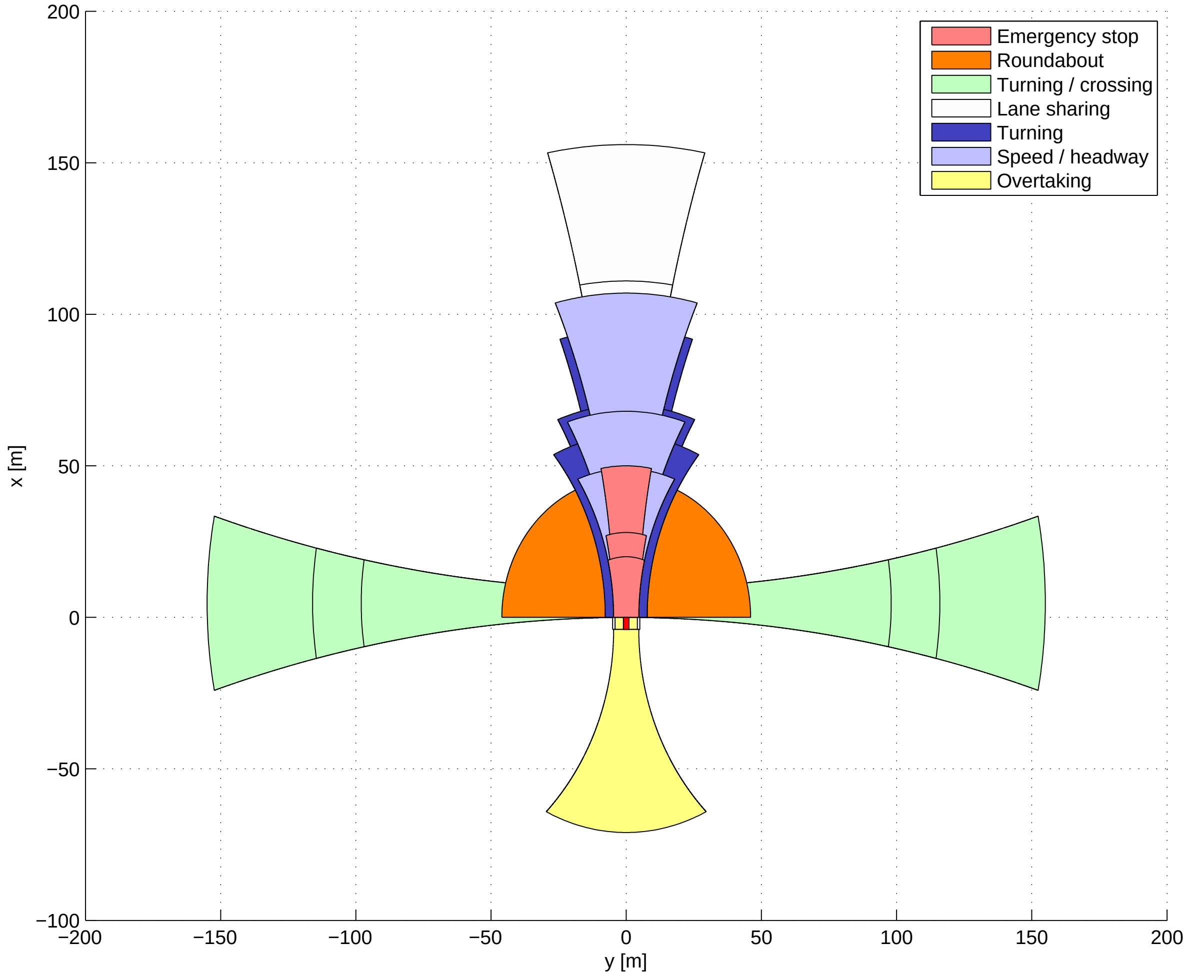


Figure 7.2: Example of limited coverage for the rural environment (R_{min} = 500 m)

7.4.3 Angular resolution / accuracy

A decent angular accuracy is required to enable lane localization, the process of determining in which lane a detected vehicle is. A low angular accuracy could lead to a vehicle being localized in the wrong lane. The effects of angular resolution and accuracy are proportional to the distance. Imagine we need a lateral accuracy of 1 m, at a distance of 100 m. For this 1 m lateral accuracy, the relationship between the required angular accuracy and the distance is plotted in figure 7.3. It should be noted that the exact same relationship is valid for angular resolution, but for convenience we will stick to the example of angular accuracy.

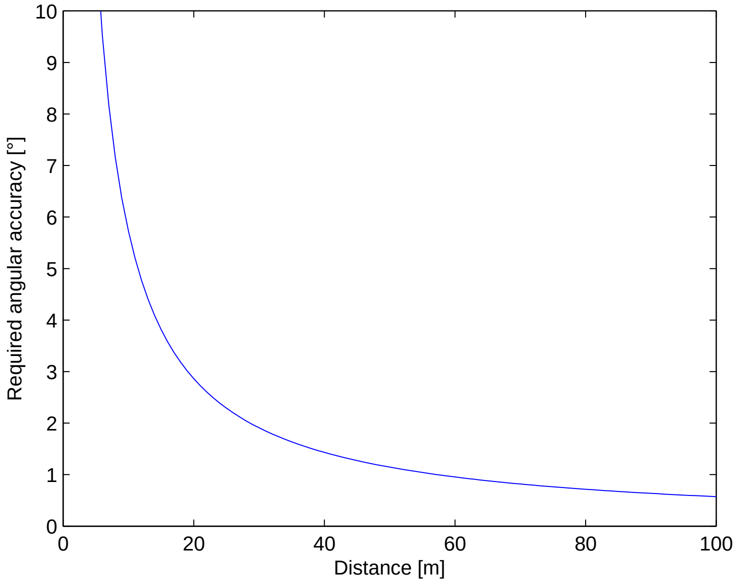


Figure 7.3: Relation between required angular accuracy and distance

Figure 7.3 shows that a small variation in the angular accuracy can have a big impact on the effective range that can be covered. Furthermore, in our assumption we have neglected the effects of errors in the heading measurement of the host vehicle. Equation 4.7) shows that any error caused by ego heading measurement error would directly affect the required angular resolution. Simply put, if we need an angular accuracy of 1 ° but our measurement error is 0.3 °, then the chosen sensor has to have an angular accuracy of at least 0.7 °. Heading measurement errors have to be kept to a minimum for our calculated metrics to be valid.

Figure 7.4: Integrated vehicle and lane boundary detection (source: [74])

There is a different approach to this problem however. Vision sensors are able to detect both lane boundaries and vehicles from the same image, as was done in [74]. Their method determines the vehicle position w.r.t. the detected lane markings, as shown in figure 7.4. This method eliminates the effects of position and heading errors. The major drawback of this system is that it needs to detect the lane boundaries, otherwise the system is not able to determine in which lane a vehicle is. However, since most roads (especially highways) have clear lane markings, such a system could be an extra layer of robustness.

7.4.4 Sensor fusion as a solution

In order to overcome drawbacks of specific sensors, sensor fusion can be used, which allows for a more robust system. A commonly used combination is RADAR and vision. The RADAR can identify targets and determine the range and relative speed. The vision system can use the RADAR data to narrow its search area which allows for better and faster object recognition. The good angular resolution of the vision system compensates for the typically poor angular resolution of the RADAR. The vision system also serves as a check to eliminate ghost targets that the RADAR picks up. Stereo vision could serve as an extra depth check alongside of the RADAR at low ranges (<40 m), however this would be at the cost of heavy image processing.

7.4.5 Other possible solutions

So how can we solve these problems? The obvious answer is to employ better sensors or to use sensor fusion to enhance sensor performance, but we can also take a look at it from a decision-making perspective. By employing a different strategy, the system could become able to cover a certain scenario even though it doesn't necessarily meet the initial requirements. These strategies usually come with significant drawbacks however, which have to be carefully considered. In this section we will mention some of these strategies. It should be noted that these are purely theoretical strategies with no mathematics to back them up, nevertheless they can be a good starting point to solve requirements issues.

Consider the 'emergency stop scenario' on a highway road. If a stationary object is present in the ego lane, then the host vehicle should either come to a full stop or perform a lane change maneuver to avoid a collision with the object. If the required angular resolution is not met, then the system is not necesarilly able to distinguish between two vehicles driving (or in this case being stationary, i.e. the end of a traffic jam) next to eachother. If the angular accuracy is not met, then the system might not be able to determine in which lane a vehicle at the distance required to perform a full braking maneuver, which could lead to the system braking for an object that's not even in the same lane. A simple strategy would be to perform the full braking maneuver anyway and to either abort or continue the maneuver once the object gets closer. The major drawback of this strategy would be that it can lead to unnecessary hard braking, which in turn could scare other (human) drivers and lead to dangerous situations. One has to carefully consider the consequences of the use of such a strategy before employing it in the car.

In rural environments, a vehicle frequently has to deal with intersection with traffic approaching from the left and right at 80 km/h, which results in large range requirements, and in turn high angular resolution / accuracy requirements. Not meeting the required angular resolution could result in two approaching vehicles being perceived as one. Not meeting the required angular accuracy could result in the approaching vehicle being perceived in a wrong lane. However, one could employ a conservative strategy: simply wait if any incoming vehicle is detected, no matter what lane it or how many of them there are in view. Although this could technically lead to unnecessary waiting time, this would be a safe strategy to employ since it doesn't involve any added risk.

7.5 Comparison to other research vehicles

We have derived the required detection coverage for Highway and Rural environments, at it makes sense to compare this coverage to the sensor sets or coverage used by other vehicles. Unfortunately manufacturers and research institutes are very hesitant when it comes to publishing such information. The only vehicle we can really compare it to is the Mercedes S 500 Intelligent Drive, as discussed in section 2.3. This vehicle's sensor layout is shown in figure 7.5.

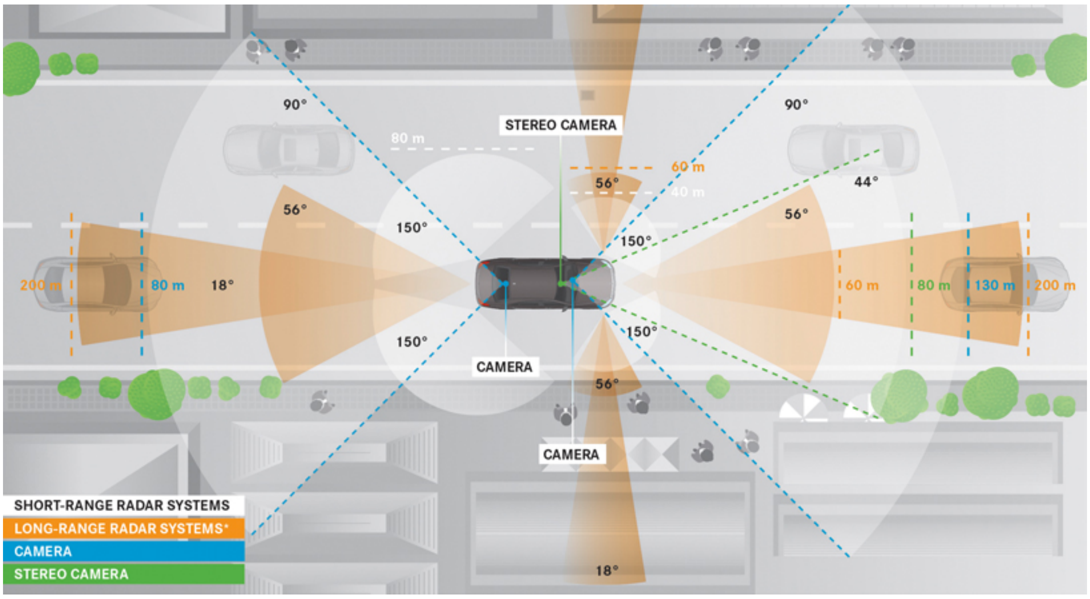
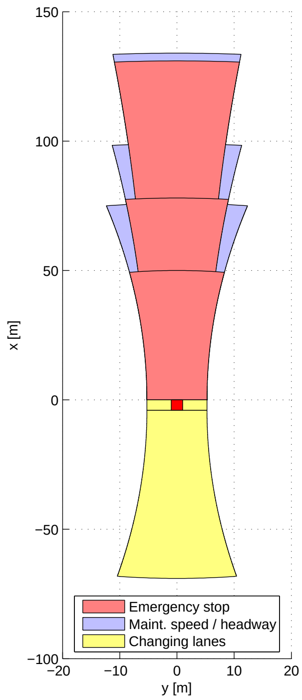
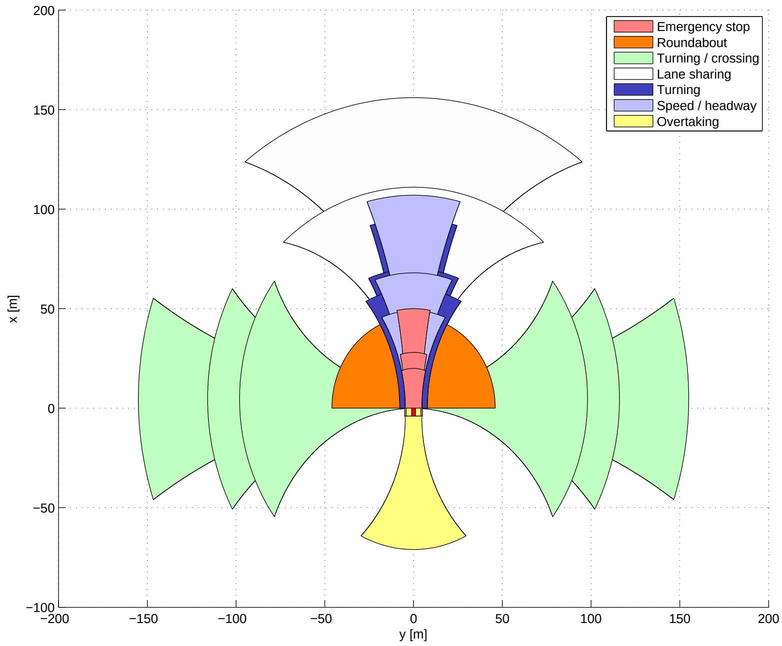


Figure 7.5: Sensor layout of the Intelligent Drive vehicle (source: media.daimler.com). Overlap of sensors is much greater in reality [57].



(a) Highway



(b) Rural

Figure 7.6: Required coverage for the Highway and Rural environment

Figure 7.6 shows (again) the required detection coverage derived earlier in this thesis, for both the Highway and Rural environments. When we compare this figure to figure 7.5, we see many similarities. The RADAR sensors used on the Mercedes cover the four 'branches' that are visible in figure 7.1 as well. According to [24], the RADAR beams on the S 500 are electronically steerable, which suggests the actual area that the vehicle can cover is even bigger than what's shown in section 2.3. The main difference is in the backward-facing RADAR sensor. A long-range model was used while a much lower range is required according to our findings. A possible explanation is that this vehicle is designed for the German highway system, which has no speed limit, which could lead to cars overtaking at very high relative speeds.

7.6 Digital maps

A digital map system can provide a large amount of information to an automated vehicle. Examples are the number of lanes, the location of intersection, speed limits, etc. The automated vehicle can simply access this information using its GPS location. This information allows an automated vehicle to know anticipate for a situation that is about to come but can't be detected by the sensors yet, i.e. braking for an upcoming intersection or roundabout. In our opinion, digital maps are an essential aspect of automated driving, as it adds another layer or safety and robustness to the system.

Chapter 8

Conclusion

Although the field of autonomous driving is a very active research area, a limited amount of information is published for corporate reasons. As part of our from-the-ground-up approach, different sensor types were identified and their characteristics and drawbacks investigated. Every type of sensor has its typical strengths and weaknesses which have to be taken into account. Furthermore, sensing requirements have been derived for both the highway and rural driving environments, by examining different driving scenarios typical to those environments. For all these scenarios, requirements were derived in terms of range, coverage, angular accuracy and angular resolution.

Current ADAS systems and autonomous research vehicles mainly use the combination of RADAR and vision systems, and use sensor fusion to compensate for sensor drawbacks. LIDAR is used less frequently due to higher cost and the heavy processing required, for mapping purposes however it is the most popular sensor. Ultrasonic sensors, due to their limited range, are used for parking systems and to complement RADAR / LIDAR / vision sensors, which can all experience issues at short distances.

The highway environment has proven to be the least complex of the two environments, and automating this environment with current technology is possibe according to our calculations. However, the sensing requirements for the highway environment are already quite demanding and are approaching the limits of what current technology is able to offer, especially in terms of angular accuracy and angular resolution. We have shown that any errors in position and heading measurements directly result in more demanding sensing requirements, which should be taken into account when one selects a sensor set based on our findings. We can only guarantee highway automation if the influences of other errors, such as ego heading error and ego position error, are kept to a minimum. Furthermore, RADAR sensors lack the necessary resolution for nearly all scenarios, but this problem can be solved using fusion with vision, a technique already widely used in current ADAS applications and encountered in several research papers.

The rural environment presents even more challenging requirements, and the 'overtaking again direction of traffic' requires a sensing range far bigger than any sensor currently on the market is able to achieve, hence this scenario can't be covered using current sensing technology. Other scenarios could be covered in theory according to our calculations, but a major problem is that current pedestrian, cyclist and animal detection systems are not robust enough to guarantee safe detection. Because of this, we think it is unsafe to automate a vehicle in areas where pedestrians and cyclists directly share the road with vehicles. Control should be handed back to the driver when such scenarios are encounted. There is also the possiblity of an animal blocking the road, which is a rare event, however it can occur on any rural road. This means we simply have to deal with this risk if we want to use the vehicle on rural roads, and the human driver should always be ready to intervene and take back control if such an event occurs.

The main limitation of this thesis is the purely theoretical approach. Furthermore, control algorithms used on a vehicle might result in more demanding sensing requirements that we haven't taken into account. Further verification through simulation is recommended, as well as road testing. However, the information gathered in this can be used to build a prototype vehicle, and we believe that it provides a good starting point for anyone that has to select a sensor set for an automated vehicle.

Finally, one should not forget that automotive sensors have seen tremendous improvements during the last decade, and will continue to improve. Many (large) companies are investing in the field of automated driving, which fuels the development of new technology. Requirements that can't be met now might be within reach when new products and technologies find their way to the market. The requirements presented in this thesis will remain valid in the future (unless serious changes in speed limits or road construction regulation occur), and can there be used to assess the capabilities of future technology.

Chapter 9

References

[1] Dined anthropometric database. http://dined.io.tudelft.nl/dined/nl/.

[2] ISO/DIS 15622. Road vehicles - adaptive cruise control systems - performance requirement and test procedures. 2000.

[3] ADAC. Comparative test of advanced emergency braking systems. www.activetest.eu/pdf/adac_aebs_report_en.pdfâĂİâĂİ.

[4] Jennifer Alexander, Philip Barham, and Ian Black. Factors influencing the probability of an incident at a junction: results from an interactive driving simulator. *Accident Analysis & Prevention*, 34(6):779–792, 2002.

[5] Audi. Side Assist. http://www.audi.com.au/au/brand/en/models/a6/a6_sedan/equipment/safety/audi_side_assist_including_audi_pre_sense_rear.html.

[6] Autoliv. Night Vision. http://autolivnightvision.com/.

[7] Nieuwe Ontwerprichtlijn Autosnelwegen. Publication isbn 90 3693 636 5. rijkswaterstaat adviesdienst verkeer en vervoer, 2007.

[8] Arne Bartels, Marc-Michael Meinecke, and Simon Steinmeyer. Lane change assistance. In Azim Eskandarian, editor, *Handbook of Intelligent Vehicles*, pages 729–757. Springer London, 2012.

[9] Oliver Bartels, Tobias Langner, Andres Aparicio, Paul Lemmen, and Carmen Rodarius. Deliverable 1.2. Technical report, ASSESS project, 2010.

[10] A Bartsch, F Fitzek, and RH Rasshofer. Pedestrian recognition using automotive radar sensors. *Advances in Radio Science*, 10(4):45–55, 2012.

[11] BMW. Active Cruise Control with Stop&Go function). http://www.bmw.com/com/en/insights/technology/technology_guide/articles/active_cruise_control_stop_go.html.

[12] BMW. BMW at the Consumer Electronics Show (CES) in Las Vegas 2014 . https://www.press.bmwgroup.com/usa/pressDetail.html?title=bmw-at-the-consumer-electronics-show-ces-in-las-vegas-2014&outputChannelId=9&id=T0163066EN_US&left_menu_item=node__5238.

[13] Luca Bombini, Pietro Cerri, Paolo Medici, and Giancarlo Alessandretti. Radar-vision fusion for vehicle detection. In *Procs. International Workshop on Intelligent Transportation*, pages 65–70, 2006.

[14] Werner Brilon, Ralph Koenig, and Rod J Troutbeck. Useful estimation procedures for critical gaps. *Transportation Research Part A: Policy and Practice*, 33(3):161–186, 1999.

[15] ZJ Chong, B Qin, T Bandyopadhyay, MH Ang, E Frazzoli, and D Rus. Synthetic 2d lidar for precise vehicle localization in 3d urban environment. In *Robotics and Automation (ICRA), 2013 IEEE International Conference on*, pages 1554–1559. IEEE, 2013.

[16] Erik Coelingh, Andreas Eidehall, and Mattias Bengtsson. Collision warning with full auto brake and pedestrian detection-a practical example of automatic emergency braking. In *Intelligent Transportation Systems (ITSC), 2010 13th International IEEE Conference on*, pages 155–160. IEEE, 2010.

[17] Commissie RONA. Richtlijnen voor het ontwerpen van niet-autosnelwegen, 1986.

[18] International Electrotechnical Commission et al. Iec 60825-1: 2007-03. *Safety of laser products-Part*, 1:60825–1.

[19] Continental. eHorizon. `http://www.conti-online.com/www/automotive_de_en/themes/passenger_cars/interior/multimedia/ehorizon_en.html`.

[20] G Richard Curry. *Radar system performance modeling*. IEEE, 2007.

[21] AG Daimler. Mercedes-benz intelligent drive tecday: Networked with all senses. *TecDay, Press Information*, 19, 2012.

[22] DARPA Urban Challenge. Technical Evaluation Criteria. `http://archive.darpa.mil/grandchallenge/docs/Technical_Evaluation_Criteria_031607.pdf`.

[23] Frederick E Daum and Robert J Fitzgerald. Importance of resolution in multiple-target tracking. In *SPIE's International Symposium on Optical Engineering and Photonics in Aerospace Sensing*, pages 329–338. International Society for Optics and Photonics, 1994.

[24] JÃijrgen Dickmann. How we gave sight to the mercedes robotic car. *IEEE Spectrum Online, Juli*, 2014.

[25] Dienst Beheer Infrastructuur Provincie Zuid-Holland. Handboek Ontwerpcriteria Wegen Versie 4.0, 2012.

[26] Martin Distner, Mattias Bengtsson, Thomas Broberg, and Lotta Jakobsson. City safety, a system addressing rear end collisions at low speeds. In *Proceedings of the 21st International technical conference on the enhanced safety of vehicles*, number 09-0371, 2009.

[27] Piotr Dollar, Christian Wojek, Bernt Schiele, and Pietro Perona. Pedestrian detection: An evaluation of the state of the art. *Pattern Analysis and Machine Intelligence, IEEE Transactions on*, 34(4):743–761, 2012.

[28] Sinisa Durekovic and Nic Smith. Architectures of map-supported adas. In *Intelligent Vehicles Symposium*, pages 207–211, 2011.

[29] Haneen Farah. Age and gender differences in overtaking maneuvers on two-lane rural highways. *Transportation Research Record: Journal of the Transportation Research Board*, 2248(1):30–36, 2011.

[30] Haneen Farah, Shlomo Bekhor, and Abishai Polus. Risk evaluation by modeling of passing behavior on two-lane rural highways. *Accident Analysis & Prevention*, 41(4):887–894, 2009.

[31] L.G.H. Fortuijn. Bijlagen bij turborotonde en turboplein: ontwerp, capaciteit en veiligheid.

[32] K Ch Fuerstenberg, Klaus CJ Dietmayer, and Volker Willhoeft. Pedestrian recognition in urban traffic using a vehicle based multilayer laserscanner. In *Intelligent Vehicle Symposium, 2002. IEEE*, volume 1, pages 31–35. IEEE, 2002.

[33] Gaspare Galati and Gabriele Pavan. Noise radar technology as an interference prevention method. *Journal of Electrical and Computer Engineering*, 2013:4, 2013.

[34] F Garcia, A De la Escalera, JM Armingol, JG Herrero, and J Llinas. Fusion based safety application for pedestrian detection with danger estimation. In *Information Fusion (FUSION), 2011 Proceedings of the 14th International Conference on*, pages 1–8. IEEE, 2011.

[35] D. Geronimo, A.M. Lopez, A.D. Sappa, and T. Graf. Survey of pedestrian detection for advanced driver assistance systems. *Pattern Analysis and Machine Intelligence, IEEE Transactions on*, 32(7):1239–1258, July 2010.

[36] Markus Goppelt, H-L Blöcher, and Wolfgang Menzel. Automotive radar-investigation of mutual interference mechanisms. *Advances in Radio Science*, 8, 2010.

[37] Paolo Grisleri and Isabella Fedriga. The braive autonomous ground vehicle platform. In *IFAC Symposium on intelligent autonomous vehicles*, volume 7, 2010.

[38] C Grover, I Knight, F Okoro, I Simmons, G Couper, P Massie, B Smith, et al. Automated emergency brake systems: Technical requirements, costs and benefits. Technical report, Transport Research Laboratory, 2013.

[39] Erico Guizzo. How google's self-driving car works. *IEEE Spectrum Online, October*, 18, 2011.

[40] Banihan Gunay. Car following theory with lateral discomfort. *Transportation Research Part B: Methodological*, 41(7):722–735, 2007.

[41] Douglas W Harwood, John M Mason, and Robert E Brydia. Design policies for sight distance at stop-controlled intersections based on gap acceptance. *Transportation Research Part A: Policy and Practice*, 33(3):199–216, 1999.

[42] HAVEit consortium. *Deliverable D. 11.1: Function description and requirements*, 2008.

[43] Geertje Hegeman, Serge Hoogendoorn, and Karel Brookhuis. Observations overtaking manoeuvres on bi-directional roads. *10th EURO Working Group on Transportation*, pages 505–510, 2005.

[44] Michael Himmelsbach, Andre Müller, Thorsten Lüttel, and Hans-Joachim Wünsche. Lidar-based 3d object perception. In *Proceedings of 1st International Workshop on Cognition for Technical Systems*, volume 1, 2008.

[45] Marcel P Huijser, Patrick Tracy McGowen, Julie Fuller, Amanda Hardy, and A Kociolek. Wildlife-vehicle collision reduction study: Report to congress. Technical report, 2007.

[46] iMobility Forum. *Automation in Road Transport*, 2013.

[47] InteractIVe. *Deliverable D7.4 Test and evaluation plans*, 2011.

[48] ITS World Congress, New York. *ADASIS protocol for advanced in-vehicle applications*, 2008.

[49] A. Kade. Enhanced adaptive cruise control system with forward vehicle collision mitigation, October 4 2007. US Patent App. 11/391,053.

[50] Dirk Langer and Todd Jochem. Fusing radar and vision for detecting, classifying and avoiding roadway obstacles. In *Intelligent Vehicles Symposium, 1996., Proceedings of the 1996 IEEE*, pages 333–338. IEEE, 1996.

[51] Jörgen Lidholm. *Stereo vision algorithms in reconfigurable hardware for robotics applications*. School of Innovation, Design and Engineering, Mälardalen University, 2011.

[52] Qiong Liu, Jiajun Zhuang, and Shufeng Kong. Detection of pedestrians for far-infrared automotive night vision systems using learning-based method and head validation. *Measurement Science and Technology*, 24(7):074022, 2013.

[53] Xin Liu, Zhenping Sun, and Hangen He. On-road vehicle detection fusing radar and vision. In *Vehicular Electronics and Safety (ICVES), 2011 IEEE International Conference on*, pages 150–154. IEEE, 2011.

[54] P McCormack. Lidar system design for automotive/industrial/military applications. *National Semiconductor Corporation*, 2006.

[55] Abel Mendes, L Conde Bento, and Urbano Nunes. Multi-target detection and tracking with a laser scanner. In *Intelligent Vehicles Symposium, 2004 IEEE*, pages 796–801. IEEE, 2004.

[56] Mercedes-Benz. Distronic Plus). `http://www.daimler.com/dccom/0-5-1210218-1-1210321-1-0-0-1210228-0-0-135-0-0-0-0-0-0-0-0.html`.

[57] Mercedes-Benz. Networked sensor systems of the S 500 INTELLIGENT DRIVE research vehicle. `http://media.daimler.com/Projects/c2c/channel/images/1003818_1958637_724_1024_13C892_04.jpg`.

[58] Chu Cong Minh, Kazushi Sano, and Shoji Matsumoto. The speed, flow and headway analyses of motorcycle traffic. *Journal of the Eastern Asia Society for Transportation Studies*, 6:1496–1508, 2005.

[59] Takeo Miyasaka, Yoshihiro Ohama, and Yoshiki Ninomiya. Ego-motion estimation and moving object tracking using multi-layer lidar. In *Intelligent Vehicles Symposium, 2009 IEEE*, pages 151–156. IEEE, 2009.

[60] Rainer Möbus, Mato Baotic, and Manfred Morari. *Multi-object adaptive cruise control*. Springer, 2003.

[61] Tobias Möller, Holger Kraft, Jochen Frey, Martin Albrecht, and Robert Lange. Robust 3d measurement with pmd sensors. *Range Imaging Day, Zürich*, 2005.

[62] Wassim G. Najm, Raja Ranganathan, Gowrishankar Srinivasan, John D. Smith, Samuel Toma, Elizabeth Swanson, and August Burgett. Description of light-vehicle pre-crash scenarios for safety applications based on vehicle-to-vehicle communications. Technical report, NSHTA, 2013.

[63] Takashi Ogawa and Kiyokazu Takagi. Lane recognition using on-vehicle lidar. In *Intelligent Vehicles Symposium, 2006 IEEE*, pages 540–545. IEEE, 2006.

[64] Umit Ozguner, Tankut Acarman, and Keith Alan Redmill. *Autonomous ground vehicles*. Artech House, 2011.

[65] Marco Parvis and Alessio Carullo. An ultrasonic sensor for distance measurement in automotive applications. *IEEE Sensors Journal*, 1(2):143–147, 2001.

[66] Abishai Polus, Sitvanit Shmueli Lazar, and Moshe Livneh. Critical gap as a function of waiting time in determining roundabout capacity. *Journal of Transportation Engineering*, 129(5):504–509, 2003.

[67] Cristiano Premebida, Oswaldo Ludwig, and Urbano Nunes. Lidar and vision-based pedestrian detection system. *Journal of Field Robotics*, 26(9):696–711, 2009.

[68] Cristiano Premebida, Gonçalo Monteiro, Urbano Nunes, and Paulo Peixoto. A lidar and vision-based approach for pedestrian and vehicle detection and tracking. In *Intelligent Transportation Systems Conference, 2007. ITSC 2007. IEEE*, pages 1044–1049. IEEE, 2007.

[69] PSA Peugeot Citroen. Lane departure warning system developed by PSA Peugeot Citroen . `http://www.unece.org/fileadmin/DAM/trans/doc/2005/wp29/ITS-09-05e.pdf`.

[70] Peter Rieger. Range ambiguity resolution technique applying pulse-position modulation in time-of-flight scanning lidar applications. *Optical Engineering*, 53(6):061614–061614, 2014.

[71] S Paul Sathiyan, S Suresh Kumar, and A Immanuel Selvakumar. A comprehensive review on cruise control for intelligent vehicles. 2013.

[72] Martin Schneider. Automotive radar–status and trends. In *German microwave conference*, pages 144–147, 2005.

[73] SICK. Vehicle control via laser in all weather and lighting conditions). `http://www.sick.com/se/sv-se/home/pr/press_releases/Documents/innovation_37_ldmrs_en.pdf`.

[74] Sayanan Sivaraman and Mohan M Trivedi. Integrated lane and vehicle detection, localization, and tracking: A synergistic approach. *Intelligent Transportation Systems, IEEE Transactions on*, 14(2):906–917, 2013.

[75] State of Maryland, Department of Transportation, State Highway Administration. Roundabout Design Guidelines. `http://www.ite.org/traffic/documents/tcir0019.pdf`.

[76] SWOV. Factsheet headway times and road safety. `https://www.swov.nl/rapport/Factsheets/UK/FS_Headway.pdfâĂİ`.

[77] SWOV. Factsheet rotondes. `http://www.swov.nl/rapport/Factsheets/UK/FS_Roundabouts.pdfâĂİ`, 2012.

[78] SWOV. Kantstroken op erftoegangswegen buiten de bebouwde kom, 2013.

[79] Toyota. Dynamic Laser Cruise Control. `http://pressroom.toyota.com/article_download.cfm?article_id=2604`.

[80] Toyota / Lexus. Toyota Motor Corp. and Lexus Showcase Advanced Active Safety Research Vehicle at CES. `http://pressroom.lexus.com/releases/toyota+lexus+advanced+active+safety+research+vehicle+ces+jan7.htm`.

[81] Chris Urmson, J Andrew Bagnell, Christopher R Baker, Martial Hebert, Alonzo Kelly, Raj Rajkumar, Paul E Rybski, Sebastian Scherer, Reid Simmons, Sanjiv Singh, et al. Tartan racing: A multi-modal approach to the darpa urban challenge. 2007.

[82] C. Visvikis, T.L. Smith, and M. Pitcher. Study on lane change departure warning and lane change assistant systems. Technical report, Transport Research Laboratory, 2008.

[83] Volkswagen. Park Assist). `http://www.volkswagen.co.uk/technology/parking-and-manoeuvring/park-assist`.

[84] Volkswagen. Side Scan (lane change assist). `www.volkswagen.co.uk/new/touareg-nf/explore/experience/driver-assistance/side-scan-(lane-change-assist)`.

[85] Takashi Wakasugi. A study on warning timing for lane change decision aid systems based on driverâĂŹs lane change maneuver. In *Proc. 19th International Technical Conference on the Enhanced Safety of Vehicles, Paper*, number 05-0290, 2005.

[86] Josef Wenger. Automotive radar-status and perspectives. In *Compound Semiconductor Integrated Circuit Symposium, 2005. CSIC'05. IEEE*, pages 4–pp. IEEE, 2005.

[87] Bernhard Wirnitzer, Wolfgang M Grimm, Hauke Schmidt, and Roland Klinnert. Interference cancelation in ultrasonic sensor arrays by stochastic coding and adaptive filtering. In *Proceedings of the IEEE International Conference on Intelligent Vehicles*, 1998.

[88] Christian Wolff. Radar tutorial. `http://www.radartutorial.eu/01.basics/The%20resolution%20cell.en.html`.

[89] Christian Wolff. Radar tutorial. *Retrieved February*, 15:2012, 2012.

[90] Zhaohui Wu, Yanfei Liu, and Gang Pan. A smart car control model for brake comfort based on car following. *Intelligent Transportation Systems, IEEE Transactions on*, 10(1):42–46, 2009.

[91] Xuedong Yan, Essam Radwan, and Dahai Guo. Effects of major-road vehicle speed and driver age and gender on left-turn gap acceptance. *Accident Analysis & Prevention*, 39(4):843–852, 2007.

[92] Provincie Zuid-Holland. Landschappelijke vormgeving rotondes, 2012.