1 Introduction

Over time, the way people move and transport their goods on land diversified. While in ancient history, humans carried their belongings on foot or used pack animals, this changed with the invention of the wheel and, with it, the carriage. It can be traced back to the fourth millennium before Christ, mainly in the regions between Mesopotamia and the Alps, as well as between today's northern Germany and the Caucasus Mountains [1]. The path of development is not known exactly but this invention significantly facilitated daily life. As no developed road network was available at that time and steering wasn't effective, these carriages were mainly used for the transportation of heavy objects over short distances. Typical application areas were harvesting, war, or religious processions. This changed when people started to build up road networks [2]. Evidence of the first roads can be provided for 2600 before Christ in Mesopotamia. However, these were still very rudimentary. In 600 before Christ, the ancient Greeks built the first paved stone roads. Two centuries later, the Romans improved this system tremendously. They prepared the ground for the construction and built the first multilayered streets, which even implemented a drainage system. Thus, until the second century, they formed 100 000 km of roads in their former dominion [3]. The next big dream of humankind was moving wagons without horses or other animals. Hence, Isaak Newton proposed a vehicle that should work with the principle of repulsion. Water was brought to boil in a cauldron, and the carriage should be powered by the force of the vapor escaping from a pipe. Unfortunately, this force was not sufficient. Later, James Watt invented the first direct steam engine. Based on this, many different steam cars were developed, but all of them had one main problem: ineffective steering on bad, bumpy roads. Thus, they did not prevail and, at some point, were replaced by the railway. With the advantage of a guided lane, enormous energy savings could be achieved this way. Obviously, iron wheels running on iron rails caused fewer losses than wheels running on former roads, which were very bumpy. Railways were initially used for the transport of goods but later for the transportation of people as well [2]. The revolution of individual transport and the associated independence began with the patent application of the first "Motorwagen" by Karl Benz [4]. The car had a rear-wheel drive powered by a gas combustion engine and was steered by a link mounted at the single front wheel. Braking was only possible using a hand lever. Even if this vehicle was unique, it is considered the first automobile in history. Over time, the vehicle was further developed into the state we know today. By allowing fast and individual movement, it captured the whole world.

Today people dream of completely autonomously moving vehicles. For public and goods transportation, the main aim is to reduce costs, while autonomous systems increase comfort in individual transport. Like for all technical achievements, an autonomously driving system is easier to implement the less complex the environment and the system

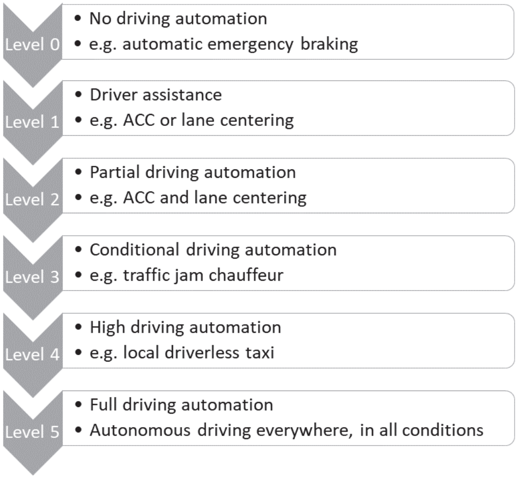


Figure 1.1: Levels of autonomous driving with corresponding example defined by SAE International 2021 [6].

itself are. Therefore, systems limited to specific applications or excluding other traffic participants can be accomplished with less effort than systems without restrictions. Railway systems, limited to the movement on a rail, with no other traffic participants than these autonomous trains and a fixed schedule, existed since the early 1980's. Automated warehouses are commonly present as well. However, problems arise with hybrid systems. This starts with automatic and person-guided vehicles to be operated in parallel in one environment. For metros, such an operation has already been successful in the city of Nuremberg in Germany in 2008 [5]. However, for road traffic, it is still a big challenge. SAE International defines six levels on how to complete automation of on-road motor vehicles [6] as shown in Figure 1.1. It starts with no automation and only emergency warning functions. Then, it continues by adding functions like adaptive cruise control (ACC) to allow then limited to finally fully autonomous driving. In Germany, autonomous driving became more tangible in 2017, when it was included in the road traffic act [7]. Before, legal aspects of highly automated driving at level three and higher were not clarified. With the amendment, approval is possible. Thus, Mercedes achieved level three admission as the first manufacturer worldwide. The “Drive Pilot” is available for the EQS and the S-Klasse model in Germany as well as in Nevada in the United States.

To put such automation functions into effect, various sensors are implemented in the vehicle to scan the environment. Such sensors are, e.g., camera and radar sensors, but to ensure good functionality, various other sensors must also be installed. Radar sensors offer the advantage of direct velocity measurements and weather as well as light independency.

They are therefore used for both short-range and long-range applications. During the development process, these sensors' recordings and the final functionalities have to be proven correct or sufficient. This can be done through real-world testing as well as through simulation. Regarding the proof of safety, experts agree that only a combination of various methods can deliver a satisfactory result [8]. However, working with radar data has one big problem. While camera data can be handled intuitively and exemplary data sets are available in a high number, this is not given for radar. Further knowledge about radar behavior in the automotive environment could improve and simplify the work on that topic. One element, present in every automotive scenario and with little available data, is any kind of road surface.

1.1 State of the Art

In this chapter, the state of the art of various topics related to this work is elaborated. This includes knowledge about radar responses on roads as well as about methods to measure them. Furthermore, currently applied methods of simulation for radar systems are of interest.

Concerning road surfaces and their behavior in terms of radar backscattering and reflection, some findings were already achieved. First, the millimeter wave (mmWave) scattering on road surfaces was analyzed for 94 GHz for various incidence angles [9, 10]. A scattering model has been developed, and a dielectric constant for asphalt as well as for asphalt covered with a thin layer of water have been determined. In [11] a permittivity value for asphalt at 77 GHz has been determined. However, no distinction is made between different kinds of asphalt, and neither are other materials roads can be made of considered. Nonetheless, there is also a study examining differences between surfaces, to be precisely between asphalt and concrete, in two conditions: directly after implementation and after being exposed to the weather for some time [12]. In addition, the backscatter coefficients of grass and roads covered with snow or during heavy rainfall are determined. Differences have been shown for these surfaces that trigger the interest to determine the behavior on other surfaces. In addition to such research regarding radar scattering and properties, the condition of a road and how to determine it using radar have been examined. This includes weather situations such as having icy, snowy, or wet surfaces instead of not affected dry surfaces. As water and ice change the backscattering properties of a road, their presence can be detected using a setup consisting of a network analyzer and a horn antenna [13, 14]. Moreover, [15] examines foreign object debris on asphalt as well as asphalt clutter. It states that the clutter does not change considerably in a frequency range between 10 GHz and 77 GHz but is attenuated for higher frequencies. Here, too, no distinction is made between different surfaces.

Besides these laboratory measurements, some approaches using airborne synthetic aperture radar (SAR) to characterize roads exist. These are not directly useful for the further development of autonomous driving but show methods on how additional data in the fields of radar and roads can be obtained separately. Such a characterization has the aim

of monitoring the condition of a road. Applications are detecting road sections where road works are necessary or warning of potholes. The functioning of such a system and its appropriate operation in the real world has already been proven. It collects and processes polarimetric SAR data in the X band. Thus, road damage can be detected [16]. The latter is not the only useful information about roads that can be gained using SAR. To improve the safety of traffic participants, SAR data can be employed to estimate the general roughness of a road as well as its changes. In this approach, airborne SAR data is analyzed, and the obtained roughness is linked to a map [17].
Another field where the radar reflection of roads is used is cartography. SAR data is used a lot for surveying the earth. To keep maps up-to-date, SAR images recorded by satellites are analyzed, and e.g. roads can be extracted automatically. The segmentation for the detection of the roads is either done using classical computer vision algorithms [18] or by employing deep learning methods [19]. These measurements are performed at lower frequencies than in automotive radar systems but show again the appropriateness of using SAR for road classification at mmWave applications.
Finally, the state of the art of simulation of radar systems for automotive applications has to be considered. As these systems are complex, mainly ray tracing approaches are used. The modeling is done in different levels of complexity. Some use only geometrical optics, not differentiating between varying materials [20]. Others implement material properties in their simulations [21]. However, such an implementation is very basic and distinguishes, e.g. only between conducting and not conducting materials. In addition, approaches for increasing the accuracy of radar systems exist, which add a simulation, e.g., of fast diffraction variations at certain points in a second step of the simulation algorithm. For this purpose, integral equations have to be solved [22]. Anyways, scenarios containing such problems are rather few for automotive radar. It could be applicable, e.g., for the simulation of vegetation.

1.2 Goals and Content of this Work

This leaves several questions that should be answered as the goal of this work. First, in general terms, how does the behavior of radar waves differ for an incidence on different road surfaces? Is it enough to differentiate two or three categories of road surfaces as done until now, or can further variation be detected? This also raises the question of which road surfaces are typically found on highways in Germany. From this follows the question of the radar reflection behavior of them. For which angles occur diffuse and for which specular reflection? How can the corresponding reflection behavior be measured, and how can it be described? Which physical parameters are suitable for the characterization? Furthermore, how does the behavior differ for the same road material types but with different material compositions? In this context, a laboratory measurement setup using drill cores as samples is used to characterize the diffuse scattering which can be found in chapter 3. The roughness of the road surfaces and, with it the angle where the reflection type changes, is measured using an area of sands method. The corresponding results, as well as an analysis regarding specular reflection, are presented in chapter 4. For specular reflection, an openspace measurement setup is introduced. With the corresponding signal model, relative permittivity values for certain surfaces are determined and summarized in this chapter as well. In the end, one has to think about how to share and spread such findings. This includes the question for an appropriate structure of the database and the corresponding data format. The focus here should be on making the database available to the broad mass of scientists and developers. The provided data should be compatible with standard simulation tools in order to reduce the barriers to utilization. Through widespread usage, the data can be verified and extended. It can also be used to check for the need for additional required data to grow a dataset, including main material parameters for the automotive simulation. Such a database is introduced in chapter 5.

The whole work is structured in two main blocks. Chapters 3 - 5 cover the actual new topics like the measurement results as well as the specific measurement setups or samples that are used to obtain any results. Generally valid information, such as measurement principles or differences in road surfaces, is introduced in chapter 2. Not relevant basics are neglected for this work, and the reader is referred to the relevant primary literature. The necessary passages are cross-referenced in each case to facilitate easy reference if required.

Finally, a summary of all conclusions and an outlook for possible future work can be found in chapter 6.

2 Fundamentals and First Estimates

In this chapter, the fundamentals regarding all fields of expertise relevant to this work are introduced. Aspects that have only a peripheral influence on this work are deliberately omitted. Nevertheless, aspects, which could have an impact, are discussed, as well as why some of them actually don't have to be considered in this work. Beginning with some important aspects about electro magnetic (EM) waves in general, we will move on to radar basics. The scope of this work is limited to frequency modulated continuous wave (FMCW) radars, only concentrating on the main working principle and on automotive sensors. Of importance as well is the penetration depth of a wave into the ground as the behavior of the wave while hitting the ground is to be specified. A second setup uses the principle of SAR. Therefore, it is introduced here, too. The following block deals with road surfaces, their composition, and their installation. Furthermore, it summarizes the extraction of surface probes like those which are analyzed in chapter 3. In addition, material properties and their influence on the propagation of EM waves when being hit as well as the determination of important parameters are elaborated on. To some extent, the determination of these parameters is explained. Finally, some probability density functions are outlined as these are used to get a mathematical description of the scattering measured with the SAR setup.

2.1 Electromagnetic Waves

In general, an EM wave can occur when an electric charge is accelerated. A change in the electric field is caused, and consequently, a change in the magnetic field as well. This results in an oscillation, the EM wave. Independently of this source, it can continue traveling once its propagation starts depending on the environment with which it can interact. The behavior of electric and magnetic fields is described by the Maxwell equations. Such waves carry momentum and energy but never any matter and can propagate in materials as well as in vacuum [23]. They are defined by four properties: their frequency, propagation direction, amplitude, and polarization. The first three of them are characteristics that other types of waves have as well. For example, sound waves are not polarized but have a frequency, a direction of propagation, and an amplitude. However, polarization exists only as a property of EM waves. In nature, an unpolarized EM wave can occur, but every human-generated EM wave has a polarization [24]. However, this can be a mixture of various polarizations. The spectrum of EM waves covers low frequency engineering over high frequency engineering to the different ranges of light, X-rays, and gamma rays. The here discussed radar waves belong to the mmWave spectrum, which refers to the corresponding wavelength. Nonetheless, for EM

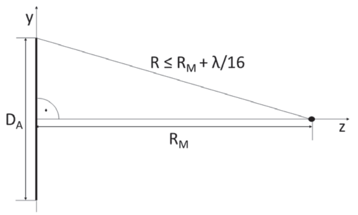


Figure 2.1: Far-field condition by means of an example of a linear antenna. Adapted from [25]

waves it applies that all of them are transverse waves. This means that the oscillation direction and, therefore, the orientation of the fields are perpendicular to the direction of propagation.

2.1.1 Plane Wave and Far-Field Condition

A good approximation for waves in the far-field, simplifying their analysis, is the concept of a plane wave. As the name says, these are waves with planes as phase fronts. These planes are perpendicular to the direction of propagation, or respectively the normal vector of these planes is the wave vector.
However, such an approximation can only be taken for far-field conditions. Having a point source in space, a spherical wave is emitted. Obviously, the phase fronts are curved, but the further away an observer is, the weaker the phase curvature appears. If the observer is far enough away, the phase front appears to be a plane. This connection leads to different ways how an EM wave can be described. For scattering problems, the space is typically divided into two or three zones. These are the near-field and the far-field, which are mostly supplemented by the Fresnel region as a transition zone in between the other two zones. The division can be done using the Fraunhofer approximation. The near-field is the zone directly after the antenna up to a distance R as in Eq. 2.1 where the curvature is high.

$$R \geq \frac{{D_A}^2}{2\lambda} \tag{2.1}$$

In the Fresnel region, the curvature becomes weaker. This transition zone is limited by the distance where the phase error between the smallest and the greatest connection from the antenna to the target is not greater than 22.5° or, respectively, the path difference is smaller than the sixteenth path of the wavelength. For clarification, Figure 2.1 can be considered. It shows a linear antenna on the left side with an antenna length D_A. The target point on the right side has the least distance R to the antenna at its center point and the longest distance R to the edge of the antenna at $D_A/2$. As described before, the far-field condition limits the path difference between those two distances on $\lambda/16$. Thus, to reach the far-field, both Eq. 2.2 and Eq. 2.3 must be satisfied [25].

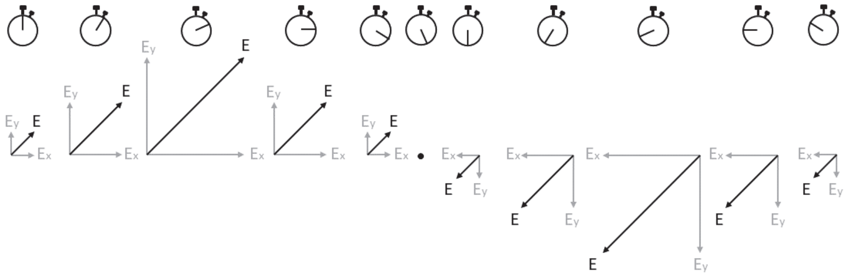


Figure 2.2: Electric field phasor changing over time for a linearly polarized wave in the first and third quadrant. Adapted from [27]

$$R \geq \frac{2{D_A}^2}{\lambda} \tag{2.2}$$

$$R \gg \frac{\lambda}{2\pi} \qquad \text{or respectively} \qquad R \geq 2\lambda \tag{2.3}$$

For some applications, the Fresnel zone is ignored as specified in the Bundesamt für Sicherheit in der Informationstechnik Technical Guideline for Electromagnetic Shielding of Buildings [26]. With the given antenna length for each measurement system and a maximum frequency of 81 GHz as described in detail in section 2.2.2, the far-field condition is fulfilled for a minimum distance of at least 60 mm. In addition, the size of the target has to fulfill these conditions as well. In this work, the size of the targets is also small enough in relation to the distance to the sensor that far-field conditions can be supposed. Therefore, it can be assumed that all waves are plane waves.

2.1.2 Polarization

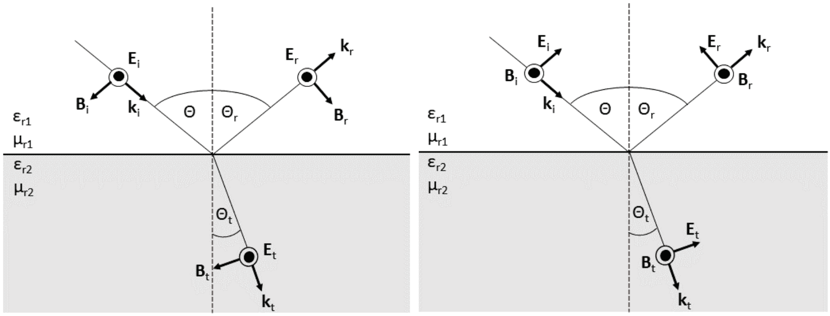
Another important property for the characterization of an EM wave is the polarization. The polarization of an EM wave is the parameter that gives information about how the electric field is orientated. The simplest case is linear polarization. For linear polarization, the orientation of the electric field is constant but changes its sign and its amplitude over time periodically, as shown in Figure 2.2. Assuming that a wave propagates in z-direction, a linear polarized wave can have electric field components in x- and y-direction, resulting in the electric field given in Eq. 2.4 for both components being in phase.

$$\tilde{\mathbf{E}}(z,t) = (E_{0x}\mathbf{e_x} + E_{0y}\mathbf{e_y})\cos(kz - \omega t) \tag{2.4}$$

For x and y components being out of phase by 180° as in Eq. 2.5, linear polarization applies as well.

$$\tilde{\mathbf{E}}(z,t) = (E_{0x}\mathbf{e_x} - E_{0y}\mathbf{e_y})\cos(kz - \omega t) \tag{2.5}$$

The use of horizontal and vertical polarization is very intuitive because the reference area is the earth's surface. Hence, the E-field of a horizontally polarized wave has the



(a) Electric field perpendicular to the incidence plane. Adapted from [27]

(b) Electric field parallel to the incidence plane. Adapted from [27]

Figure 2.3: Two cases of an EM wave incident on a dielectric material boundary.

orientation of the horizon. Thus, it is parallel to the earth's surface, and for vertical polarization, the E-field is oriented perpendicularly to the earth's surface. Furthermore, an EM wave can be circularly or elliptically polarized. The electric field phasor does not change its magnitude for circular polarization but rotates in the xy plane over time. As a result, the wave propagates in a spiral. The rotation can be clockwise, which is called right-circular polarization, or counterclockwise, which is named left-circular polarization. In both cases, the wave moves towards the observer. For elliptic polarization, the electric field vector changes its magnitude and rotates in the xy plane over time. Here, too, the rotation can take place in both directions. For details regarding nonlinear polarization, the reader is referred to the literature as the cases considered here always show linear polarization. Every polarization state can be obtained as a linear combination of two orthogonal polarization states, and precisely one orthogonal state exists for every polarization state. This must be taken into account during measurements as polarization influences the reception of a wave at an antenna. If an antenna is orthogonally polarized compared to the arriving wave, no signal can be received [24, 27].

2.1.3 Incidence at a Dielectric Surface

For a plane wave hitting a plane boundary surface to a material with different material parameters, one has to distinguish between two different cases. The terminology can be confusing, in combination with the standard definition of horizontal and vertical polarization, which is why one has to pay particular attention. For the differentiation, the orientation of the electric field regarding the drawing plane is used as a reference plane. Consequently, case one considers the electric field being perpendicular to the drawing plane as shown in Figure 2.3a. The relative permittivity of the materials is distinct ($\epsilon_{r1} \neq \epsilon r2$), and the relative permeability is one for nonmagnetic materials ($\mu_{r1} = \mu_{r2} = 1$). These material properties are defined in section 2.4.1. On the other