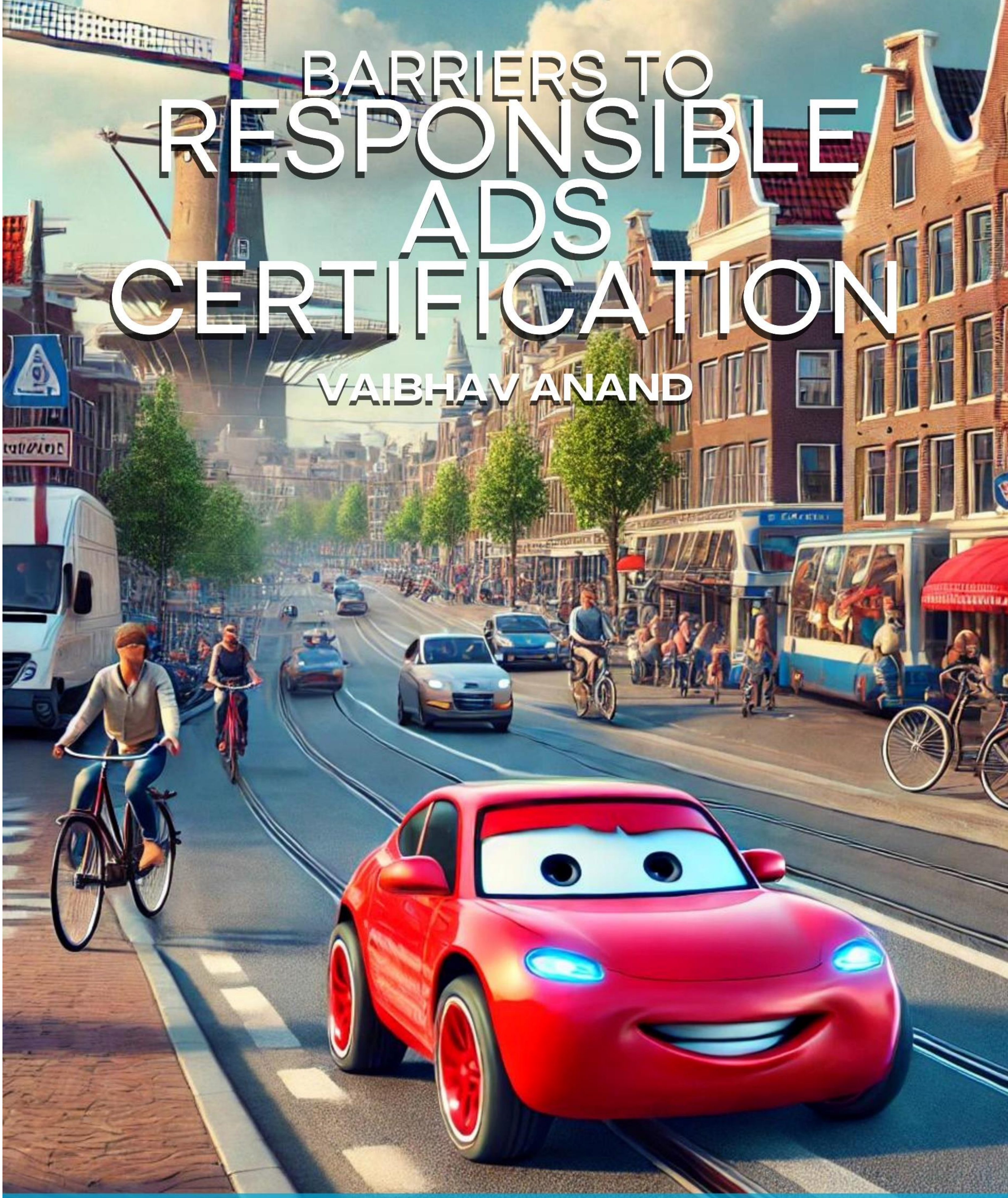
BARRIERS TO RESPONSIBLE ADS CERTIFICATION

VAIBHAV ANAND



RDW

Dr. Eleonora Papadimitriou
Dr. Jan Anne Annema

Dr. Simeon Calvert
Shubham Koyal

TU Delft

What are the barriers to responsibly certifying ADS on Dutch roads?

Master Thesis Report

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Vaibhav Anand
Student number: 5739489

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Rijksdienst voor het Wegverkeer (RDW)

Graduation Committee

Committee chair:	Dr. J.A. (Jan Anne) Annema
1st Supervisor:	Dr. E. (Eleonora) Papadimitriou
Advisory Supervisor:	Dr.ir. S.C. (Simeon) Calvert
Company Supervisor:	Shubham Koyal

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Preface

Cars have been an obsession of mine for as long as I can remember. From growing up on HotWheels to becoming an engineer because of Formula Student and stepping into project management through an off-roading startup, this four-wheeled art piece has shaped me and my personality. Growing with the automotive industry and having the opportunity to work on the future of cars has been a dream come true. My motivation letter to MOT started with Murphy's law. Many things went wrong throughout these two years, and I could not have navigated without the people in my life. I have grown so much because I have had the chance to experience and learn from extremely radiant personalities. This page is dedicated to everyone who helped me grow. Thank you, TU Delft, for being an icon. Thank you, library, for being a constant.

Writing this thesis has been a test of more than just my academic aptitude, as this is one of the first projects of this solitude that I started and actually completed. To everyone who shared a coffee or dinner with me and listened to my endless rants, you are why I pushed through, and I hope you know that. I found my family away from home in BEST, which somehow attracts the most amazing people. My RM core team, the Kool Kids, my couch-crashers across Europe, and so many more BESTies who believed in me more than I believed in myself—I truly value our friendships.

This thesis would not have been possible without the ingenuity of my committee. I still remember my first conversation with Dr. Jan, who started by saying that self-driving cars might never fully take over but encouraged me to proceed with optimism. His positivity and practicality are the foundation on which this report stands. Dr. Eleonora was always ready to hop into brainstorming sessions and helped me escape my thought spirals. Her insights on my approach triggered deep reflections while providing enough guidance for me to move forward. Dr. Simeon's work on ADS has been one of the building blocks of this project, and his candour has been a constant source of inspiration. The Faculty of Technology, Policy, and Management will always feel like home, and every classroom has a story to tell. Creative Facilitation and the staff behind it also hold a special place in this.

RDW has been a valuable knowledge hub, opening up their network for me. The willingness to explore vulnerabilities reflects their maturity. I am grateful for the opportunity to collaborate with RDW and to learn an entirely new side of this industry. My mentor Shubham's proactive attitude, patience in explanations, and honesty have been a weekly source of encouragement. My colleagues from Technical Innovation helped me navigate the complexities of regulations with ease and never short of insightful stories to share.

And, of course, none of this would have been possible without my family's daily check-ins. Yes, Dadi, I've eaten something today; yes, Mom, I'll catch up on sleep; and yes, Dad, I'm taking care of myself. I was not forced to write that Diya is the best. And all of this is an attempt to follow in Bua's footsteps.

Some people always know the right things to say, and my mentor, Prathamesh, is one of them. I can never thank Acceleracers enough. I still have a long list of things I am grateful for, and I'll thank you all in person soon—Recharge dinners, Breathing buddies, Faculty Student Council, Koornbeurs, Makerspace Delft, MaCo, Effective Altruism, IP, all my group project buddies and all other I shared a moment with on the way. To all the books, blogs, podcasts, and YouTubers that shaped me, this thesis also belongs to you.

Vaibhav Anand (Tru)
Delft, September 2024

Executive summary

Autonomous Driving Systems (ADS) are an innovative solution to urban mobility problems and have the potential to transform the Dutch roads radically. However, before these systems can be widely adopted, they must undergo a rigorous certification process to meet safety and reliability standards. Regulatory authorities are currently grappling with the challenge of certifying ADS responsibly. Despite significant technological progress, there is still limited understanding of the root causes behind these certification challenges. Without a clear understanding of these obstacles, finding effective solutions remains difficult. Therefore, this research aims to explore the barriers to responsible ADS certification and provide insights into how these challenges can be overcome.

Background description

The shift from human-driven vehicles to those equipped with Advanced Driver-Assistance Systems (ADAS) has marked a significant evolution in automotive technology. These modern vehicles, often categorised under Level 2 automation, are increasingly capable of performing complex driving tasks autonomously. By 2035, it is estimated that 35% of cars on the road will possess Level 3 or higher autonomous capabilities. Despite these developments, the certification processes, especially in the EU, remain varied and complex, stifling the innovative nature of this technology.

Scientific and societal significance

The potential of ADS to revolutionize transportation cannot be overstated. The technology promises social and technical benefits, including reduced traffic congestion, mobility for the physically challenged, and enhanced safety. However, the current regulatory frameworks are struggling to keep pace with these advancements, raising concerns about the responsible deployment of ADS. Addressing these challenges is not just a technical issue but has profound societal implications. The ability of ADS to improve road safety and reduce fatalities, which are currently exacerbated by human error, highlights the societal importance of this research.

Research Gap

Despite the promising potential of ADS, the regulatory frameworks do not fully address the complexities involved in their certification. There is a notable gap in understanding how to harmonise the diverse stakeholder values within a comprehensive certification framework. This research seeks to fill this gap by exploring the barriers to responsible ADS certification and proposing improvement areas to align with societal values and technological realities.

As the objective of this research is to explore the complexities surrounding ADS certification, the main research question guiding this study is:

What are the barriers to responsibly certifying ADS on Dutch roads?

Research methodology

To answer this research question, 21 stakeholder interviews were conducted, followed by a session with five stakeholders to validate priorities based on severity and complexity. The methodology primarily employs a qualitative research approach, focussing on semi-structured interviews to capture the complex narratives surrounding ADS certification. This approach was chosen for its flexibility and ability to accommodate the evolving nature of ADS technology. The sampling strategy utilised a theoretical barrier-lifecycle matrix to engage various stakeholders across the ADS ecosystem, including experts from regulatory bodies, technical developers, academic researchers, and industry consultants. The interview protocol was structured to explore four main Responsible Innovation (RI) themes- anticipation, inclusion, responsiveness, and reflexivity. The semi-structured nature of the interviews allowed for both guided discussions on pre-determined themes and the exploration of new insights as they emerged.

The grounded theory approach was employed for data analysis, which involves developing theories directly from the data collected. The analysis began with open coding, where transcripts were anonymised and broken down into units to identify recurring themes or barriers to ADS certification. This was followed by axial coding, which reconnected these units into overarching themes, leading to categories reflecting responsible ADS certification's complexities.

Results

The findings of this research reveal a significant list of barriers, and Figure 1 compiles them to serve as the foundation for prioritising the limited resources at the regulator's disposal.

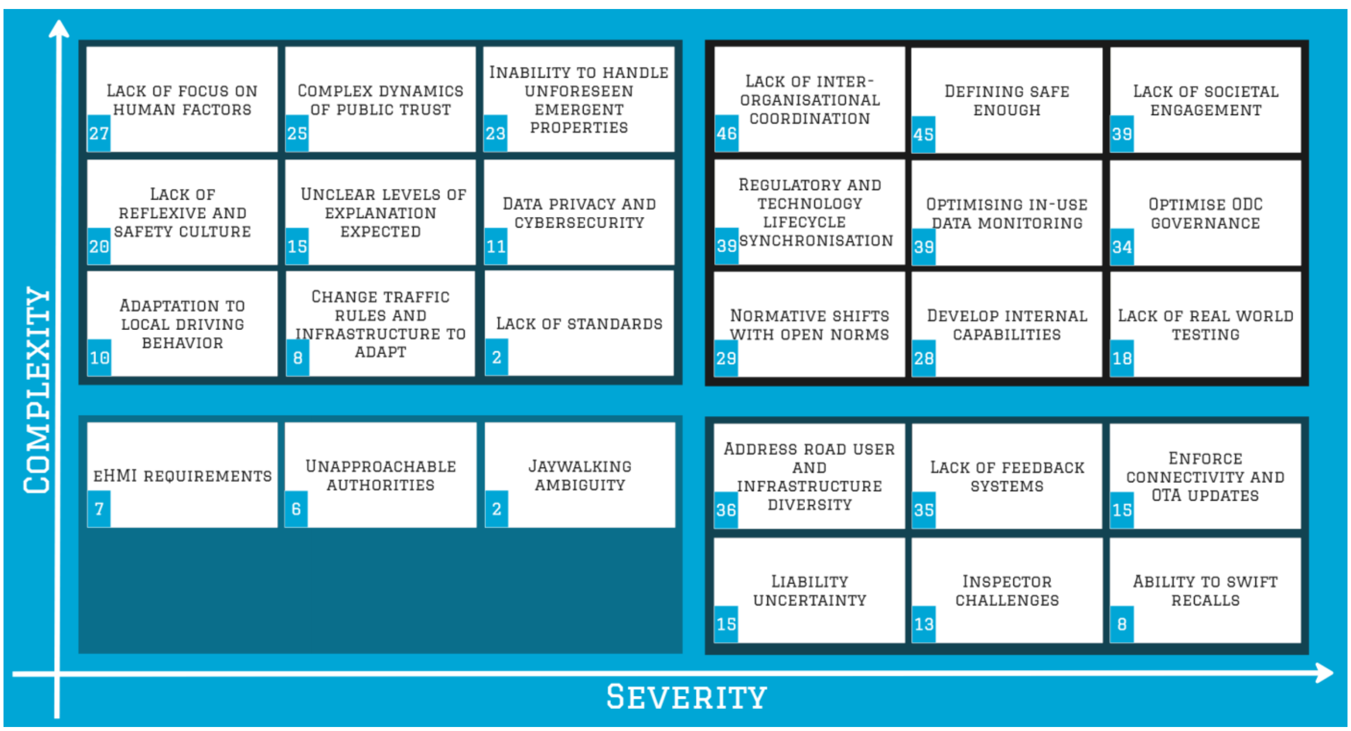

Figure 1: Barriers to responsible ADS certification on Dutch roads

The study identifies critical areas where existing regulations fall short and need improvement, highlighting the complex interplay between technical requirements and societal expectations. The results are structured around the central themes derived from the grounded theory analysis, offering a detailed exploration of each barrier. They are categorised into four quadrants based on their severity and complexity.

Emphasis on the misalignment between regulatory frameworks and the rapid pace of technological innovation was significant. Stakeholder engagement emerged as a prominent complex and social barrier alongside the development of internal capabilities and the definition of safe enough. Inherent issues such as regulatory and technology lifecycle synchronisation and normative shifts occurring with open norms are the next big chunk of barriers. The need for real-world testing alongside optimising Operational Design Condition governance and data monitoring is highlighted. The findings also revealed significant challenges in harmonising stakeholders' diverse values and priorities, which complicates the development of a unified certification framework. This misalignment, coupled with inadequate coordination among regulatory bodies, has created a fragmented landscape that hinders the efficient deployment of ADS. Additionally, the research highlighted the critical need for enhanced transparency and more robust stakeholder engagement processes to address these complexities and ensure that all voices are effectively integrated into the certification process.

Discussions

The discussion examines the barriers to ADS certification through the lens of the RI pillars. The analysis begins with anticipative barriers, where the research highlights the insufficient attention given to human factors and the complexities surrounding public trust. The unpredictability of how humans interact with ADS technology and the variability of public trust present significant challenges. Inclusion highlights the importance of engaging various stakeholders to reflect diverse societal values. Responsiveness underscores the necessity for regulatory frameworks to adapt swiftly to technological advancements. Reflexivity calls for continuous self-assessment by regulators to ensure their actions align with evolving ethical standards and public expectations.

The chapter further explores the trade-offs between safety, sustainability, and legal rigour, which are crucial considerations in regulatory decision-making. The findings reveal that regulators face difficult choices, as prioritising one aspect, such as safety, may come at the expense of others, like innovation or legal clarity. Understanding and managing these trade-offs is critical for developing a balanced approach to ADS certification that supports technological advancement and public safety.

Recommendations

The Dutch Type Approval Authority recommendations focus on strengthening organisational resilience, stimulating innovation, mandating inclusive practices, and enhancing feedback mechanisms to better handle the complexities of ADS certification. The research underscores the importance of developing internal capabilities, which is crucial for the TAA to adapt to the rapid technological advancements associated with autonomous driving systems. Effective stakeholder engagement is also vital, as it ensures that diverse perspectives are integrated into the certification process, aligning regulatory actions with societal expectations. Adopting agile governance strategies is recommended to improve the flexibility and responsiveness of the TAA, enabling it to not only refine the current certification process but also stay ahead of future technological developments. To responsibly certify ADS for Dutch roads, regulators must invest resources in addressing the barriers identified in this research, ensuring that the certification process is robust, inclusive, and capable of evolving alongside the emerging challenges of ADS.

This research aims to strengthen the regulator's understanding of the efforts required and effectiveness achieved in overcoming barriers to responsible ADS certification on Dutch roads.

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List of Abbreviations

ADAS	Advanced Driver-Assistance Systems
ADS	Automated Driving Systems
AI	Artificial Intelligence
AV	Autonomous Vehicle
CDEI	Centre for Data Ethics and Innovation
DMV	Department of Motor Vehicles
EC	European Commission
EDR	Event Data Recorder
EU	European Union
EV	Electric Vehicle
HMI	Human-Machine Interface
MHC	Meaningful Human Control
MS	Member States
OEM	Original Equipment Manufacturer
OTA	Over-The-Air
RDE	Real Driving Emissions
RDW	Road Transport Agency (Netherlands)
RI	Responsible Innovation
SAE	Society of Automotive Engineers
SPI	Safety Performance Indicators
TAA	Type Approval Authority
TS	Technical Services
UN	United Nations
UNECE	United Nations Economic Commission for Europe
UK	United Kingdom
US	United States
V2I	Vehicle-to-Infrastructure
V2V	Vehicle-to-Vehicle
V2X	Vehicle-to-Everything
VRU	Vulnerable Road User
XAI	Explainable Artificial Intelligence

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1. Introduction

Since the automobile's mass-market launch, controversies around safety have lingered, leading to a mobility history filled with continuous technological innovation. Cars have undergone significant safety improvements to protect occupants and other road users. Features like crumple zones and airbags have significantly improved road safety since the 1970s. Since the fourth industrial revolution, automobile safety and comfort features have been based on digitalisation. However, the progress in reducing road accidents has stagnated recently, with over 600 deaths and approximately 21,000 serious injuries annually on Dutch roads (Who Is in Control? 2021). In response, national and European governments have set ambitious targets to achieve 'zero deaths' by 2050 (Directorate-General for Mobility and Transport (European Commission), 2020).

Most experts believe that transportation will eventually become automated. This emergent technological behaviour was triggered in the 1970s with the anti-lock braking system (ABS), which was deemed the first autonomous driving system (Galvani, 2019)—the adoption of ABS into mainstream automotive design involved three main stages. Initial Research and Development (RnD) arrived from aviation and motorsports applications, followed by voluntary implementation by high-end manufacturers. This integration necessitated additional testing and verification during homologation (European Commission et al., 2020). Recognising the safety benefits of ABS, European regulatory bodies have mandated its inclusion in all new cars since 2004, ensuring a standard level of safety across all vehicles. A progression pattern mirroring ABS is anticipated when adapting automated driving systems (ADS). ADS is currently in the initial phase of RnD and is moving towards homologation, which requires the development of certification requirements[1].

This chapter overviews the current state of ADS certification and its broader societal context. It begins by explaining the SAE levels of automation and examines the Vienna Convention on Road Traffic, which sets the legal boundaries for what constitutes a "driver" in the context of ADS. The chapter then reviews the certification processes for vehicles currently used on Dutch roads, clarifying the standards and procedures. From there, it introduces the Responsible Innovation (RI) concept, highlighting why it is essential for ADS certification. Building on this, the chapter explores where certification efforts stand and identifies the societal benefits that successful certification can bring. This sets up a clear research gap—between the desired outcomes of a fully integrated ADS certification process and the present situation. The chapter concludes by defining the scope of the research and introducing the key research question that will guide the thesis.

[1]In this research, the term certification will be used interchangeably with homologation, type approval, and other related terminologies.

1.1 Background description

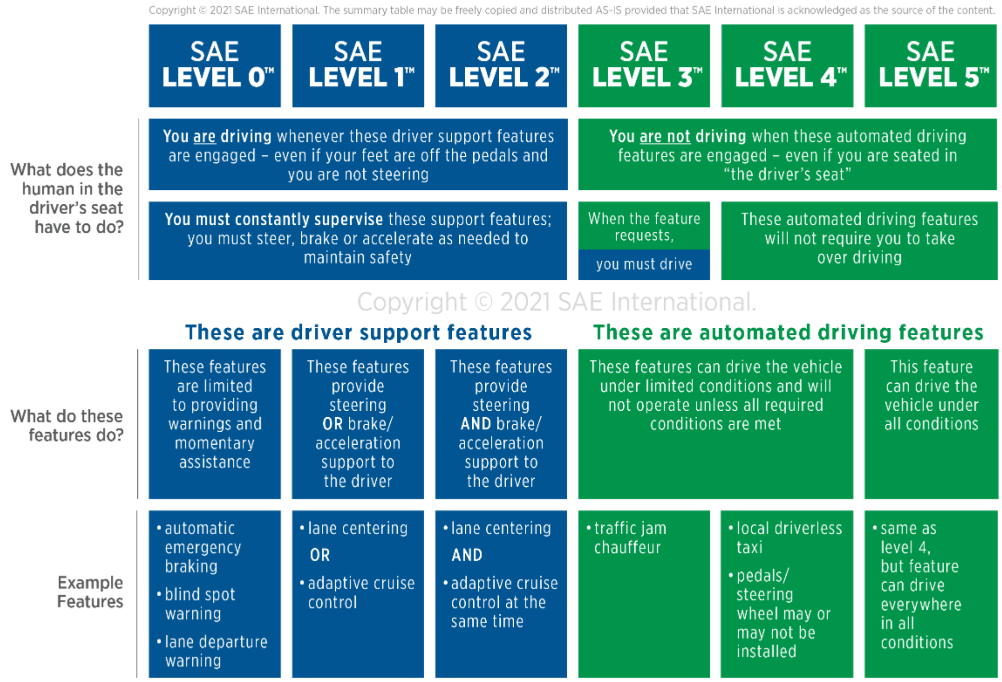

Figure 2: SAE Levels of driving automation (SAE International, 2021).

Modern cars equipped with Advanced driver-assistance systems (ADAS) represent a shift in vehicle capability compared to a few decades ago and are labelled as Level 2 by the Society of Automotive Engineers (SAE)' standard J3016. The levels classified by SAE are further explained in Figure 2. Essentially, these vehicles are becoming computers on wheels, impacting drivers, vulnerable road users (VRU), and infrastructure. This transformation represents progress and introduces unknown safety challenges, as with any significant innovation. These challenges can vary from system failures resulting from sensor malfunctions to cybersecurity threats where vehicles can be hacked, but the potential of unknown unknowns remains high (Faisal et al., 2019). By 2035, 35% of vehicles on the road will likely have Level 3 or higher autonomous driving capabilities (Deichmann et al., 2023). High-level decision-making systems provide the cognitive intelligence necessary to navigate Level 3, 4, or 5 vehicles, enabling them to make complex decisions and adapt to dynamic road conditions, mimicking a human driver.

The Vienna Convention on Road Traffic, ratified by 86 countries, including The Netherlands, has an amendment as of 2022 that now includes definitions for ADS, which uses hardware and software to collectively perform the dynamic driving task on a sustained basis, including all real-time operational and tactical functions necessary for vehicle movement. It clarified that systems influencing vehicle operation must be overridable by humans, and ADS must also conform to UN vehicle regulations (Sever & Contissa, 2024). It does not mandate that a driver must be physically present in the vehicle, but rather that they must maintain control over it without defining the nature of the control. The industrial lingo introduced by SAE differs from regulatory terminology (On-Road

Automated Driving (ORAD) committee, 2021).[2] ADS is used in this research to characterise Level 3, 4, or 5 automated motor vehicles travelling on land. As ADS certification stems from the current regulations, the following section highlights how vehicles are regulated in The Netherlands.

1.1.1 Certification on Dutch roads

Vehicles entering the EU must pass a thorough certification procedure before being sold or driven in any member state (MS). The regulatory landscape is currently characterised by a mix of EU-wide regulations and country-specific implementations, leading to a non-uniform landscape, as further discussed in 4.1. This extensive process ensures environmental and performance standards compliance, underscoring the EU's commitment to integrating the Charter of Fundamental Rights into all regulations and operations (European Union Agency for Fundamental Rights, 2012). The first stage evaluates prototypes from manufacturers in collaboration with TS for aspects such as emissions, safety features, and overall performance. After completing all specified tests, including real driving emissions tests, the vehicle is granted type approval by one of the twenty-seven national TAAs across the member states, and a certificate of conformity accompanies each vehicle produced under this approval. This harmonised certification framework facilitates the free movement of vehicles within the single market and includes measures for mass-produced and unique single-use vehicles. The EU system emphasises mutual recognition of approvals, enabling vehicles approved in one country to be legally driven throughout the EU (Regulation (EU) 2018/858, 2023; *Regulation (EU) 2019/2144*, 2019). This harmonisation would eventually apply to ADS, and the current certification process is further detailed in Appendix A.

Vehicle certification is not just limited to technical requirements; broader social implications should also be considered. The European Commission (EC) emphasises integrating responsible innovation (RI)[3] with regulatory frameworks, suggesting that ADS certification must also incorporate RI principles to ensure that ADS can be integrated into cities (European Commission, 2013; Jakobsen et al., 2019). The following section highlights the growing importance of RI and the benefits of incorporating RI frameworks into processes.

[2] According to Article 3 of EU Regulation 2019/2144, the regulation setting certification requirements for motor vehicles and their components, an "automated vehicle" can move autonomously for certain periods without continuous driver supervision but still requires driver intervention, whereas a "fully automated vehicle" can operate autonomously without any driver supervision.

[3] In this research, the term RI will be used interchangeably with Responsible research and innovation (RRI), responsible innovation and technology (RIT) and other related terminologies.

1.1.2 The need for RI

Werker (2020) highlights the need to develop measures to guarantee that these technologies are used ethically and responsibly as technology enters urban environments. Regulators play a crucial role in shaping innovation, mainly through policies that drive technological progress. However, policymakers are also responsible for ensuring these innovations align with societal values. The history of technologies like genetically modified organisms and nuclear weapons underscores this. The rapid commercialisation of GMOs in the 1990s, without sufficient ethical considerations or public dialogue, had unintended consequences, reducing public trust and slowing biotech progress (Jasanoff, 2007). Similarly, nuclear weapon development, for example, during the Manhattan Project, demonstrates how technological advances may surpass ethical monitoring, resulting in decades of geopolitical conflict and social terror (Von Schomberg, 2012). RI plays a crucial role in gaining societal acceptance of new technologies by guiding innovations that are not only transformative but also socially responsible, ensuring they reflect public values (Li et al., 2019).

This research used Stilgoe's (2013) framework to define RI into four main pillars. Similar frameworks from the EC's six keys (2015) to the political concept of RI from Schomberg & Blok (2023) exist, offering similar interpretations, but Stilgoe's concise approach effectively summarises the essential aspects. **Anticipation** addresses recognising and understanding the broader impacts of technology by envisioning possible outcomes and unintended consequences. **Inclusion** emphasises involving diverse stakeholders in the innovation process, ensuring multiple perspectives are considered. **Reflexivity** requires innovators to critically reflect on their assumptions, values, and actions, questioning how these influence innovation's direction and outcomes. **Responsiveness** focuses on adapting the innovation process in response to new insights or societal needs, ensuring alignment with public values and concerns. These pillars provide a structured approach to probe stakeholder interview questions and channel the discussion. Although idealistic ADS development should involve extensive RI frameworks, different levels of ADS vehicles are being developed, marking the innovation phase of Ortt & Schoormans's (2004) diffusion curves and their current status is further explained in the next section.

1.2 State of the art

Two primary development strategies are being pursued to achieve full autonomy: an incremental progression through the SAE levels and a direct-to-level-four approach. Traditional manufacturers like Tesla, BMW, and Mercedes typically follow the incremental path, gradually advancing through each SAE level. In contrast, start-ups such as Google's Waymo adopt the direct-to-level-four method, focussing on automated testing and aiming to offer mobility as a service (Jeffs, 2022). Another innovative approach utilises both the ADS's capabilities and the infrastructure, exemplified by Professor Sahin Albayrak's real-life test track in Berlin (Altunyaldiz, 2020). Another method to enhance ADS involves human supervision outside the vehicle. A remote assistant provides strategic or tactical guidance to the ADS, assisting in decision-making without handling operational driving tasks. Sometimes, these roles overlap, with remote operators performing fallback manoeuvres or assisting in ambiguous signal areas (Walker Smith, 2022). All these strategies need certification to ensure they meet the safety and reliability standards they promise to achieve.

In 2022, Mercedes' Drive Pilot became the EU's first fully certified Level 3 automated driving system to handle driving tasks under certain conditions, such as on the autobahn in Germany, at speeds of up to 60 Km/h. As of April 2024, only BMW's Personal Pilot L3 system has received approval for Level 3 autonomous driving on German highways with separated carriageways. But most current models with self-driving features, such as Tesla's Autopilot with "Full Self-Driving," Audi's Traffic Jam Assist, GM's Super Cruise, Ford's Blue Cruise, and Hyundai's automated driving package, are still at Level 2 (Jones, 2024). Level 4 vehicles, used in specific scenarios like shuttle buses, have been authorized in France for operation on a 600-meter public route of a medical campus (Lavars, 2023). Current driver assistance technologies are not fully self-driving, and misleading marketing by some manufacturers may cause consumers to over-rely on these systems, increasing the risk of accidents (Sever & Contissa, 2024).

Despite rapid technological advancements in ADS, the current regulatory frameworks at both the EU and national levels are insufficient, struggling to keep pace with rapid technological developments (Sever & Contissa, 2024). Tran and Le’s (2022) research conclusions outline the concerning trend in evolving ADS capabilities and the lagging regulatory frameworks, which is also evident in several other technologies.

1.3 Societal significance

Ketter et al. ’s (2023) research scrutinises the current mobility ecosystem for failing to achieve advancements in intelligent technologies and environmental sustainability. The sector contributes to global greenhouse gas emissions (28% in the EU and the U.S.). The risks associated with road traffic include urban air pollution and fatalities, with around 20,640 deaths and 1.5 million injuries in 2022 in the EU, of which ~90% were human error, as reported by the World Health Organization (2023). More than 40% of collisions involve a mix of drinking, distraction, drug use, and/or fatigue (Fagnant & Kockelman, 2015). The repercussions include less severe traffic congestion that consumes urban space and results in lost productivity hours (Cheng et al., 2020). These issues underscore the need for investments in solutions designed to overcome transportation systems' current inefficiency and unsustainability. ADS may potentially solve some of the problems raised by current human-driven solutions. While conducting the literature review described in 2.1, relevant studies highlighting the potential benefits of ADS were compiled. Five major themes were identified—Ecological, Traffic and city planning, Health and safety, Public and societal impacts, and Micro- and macroeconomic factors. Table 1 summarises the literature, which collectively underscores the multifaceted advantages of integrating ADS into modern transportation systems.

Although ADS may eventually enhance safety, it is also worth noting that their effectiveness depends on widespread adoption and reliability. In the mixed traffic interim phase with underdeveloped technology, human drivers may better manage and navigate driving environments to prevent accidents (Bertolini & Riccaboni, 2021a).

Table 1: Literature review of potential ADS benefits

Benefits theme	Causal ADS feature	Reference	Description
Ecological	Algorithmic driving	(Ketter et al., 2023), (Jungblut et al., 2023)	Lower energy consumption through optimised routing and optimising itineraries for multiple destinations
		(Sever & Contissa, 2024), (Jungblut et al., 2023)	Potential reduction in emissions through eco-driving algorithms and optimised routing supported by standardised regulations
	V2V & V2X Communication	(Fagnant & Kockelman, 2015), (Jungblut et al., 2023)	Lower fuel consumption and emissions due to improved traffic flow and reduced congestion
	V2V Communication	(Fagnant & Kockelman, 2015)	Fuel savings from road-train platooning could reduce consumption by up to 15%
		(Hardman et al., 2021)	Lower number of vehicles, resulting in reduced lifecycle emissions associated with vehicle fabrication.
Traffic& city planning	V2X Communication	(Ketter et al., 2023), (Bahrami, 2019), (Fagnant & Kockelman, 2015), (Caballero et al., 2023)	Reduced congestion through real-time coordination, leading to smoother traffic flows and increased lane capacity
		(Fagnant & Kockelman, 2015)	Optimised intersection management could nearly eliminate delays and reduce fuel consumption.
	V2V Communication	(Hardman et al., 2021)	Increased vehicle occupancy through automated carpooling, leading to fewer vehicles on the road.
		(Shladover & Nowakowski, 2019a)	Reduced emergency response times by enabling emergency vehicles to communicate with ADS, clearing traffic more efficiently
	Level 5 automation	(Fagnant & Kockelman, 2015)	Reduction in parking costs due to less need for parking spaces in urban areas
		(Bahrami, 2019)	Decreased need for parking space by 62% through optimised AV parking layouts and vehicle stacking. The reduced need for extensive road infrastructure allows for reimagining urban planning with more green spaces and pedestrian areas.
Health and safety	Perception and detection	(Ketter et al., 2023), (Pettigrew et al., 2018), (Caballero et al., 2023), (Shladover & Nowakowski, 2019a)	Enhanced safety through crash avoidance systems, better detection of objects and environmental conditions
	Algorithmic driving, Perception and detection	(Sever & Contissa, 2024)	Improved decision-making capabilities in complex traffic scenarios through enhanced sensor fusion and AI algorithms
	Reduced human reliance	(Wu et al., 2021), (Pettigrew et al., 2018), (Shladover & Nowakowski, 2019a)	Reduced crashes by eliminating human error
		(Fagnant & Kockelman, 2015)	Reduction in fatal crashes by at least 40% due to elimination of human errors like fatigue and distraction
		(Fagnant & Kockelman, 2015)	Minimized reaction time and error due to faster AV responses
		(Wu et al., 2021)	Improved mobility for people with disabilities

Public and societal	Level 5 automation	(Fagnant & Kockelman, 2015)	Increased mobility for the elderly and disabled, reducing social isolation
		(Harper et al., 2016)	Non-drivers might boost total light-duty vehicle miles travelled by up to 9%, resulting in higher mobility for previously neglected communities.
		(Fagnant & Kockelman, 2015)	Expanded car-sharing and ride-sharing opportunities, reducing the need for personal vehicle ownership
		(Kyriakidis et al., 2015a)	Increased engagement in secondary tasks such as resting, watching movies, or reading during fully automated driving, enhancing passenger comfort and productivity.
	Level 3+ automation	(Hardman et al., 2021)	Increased long-distance travel by 36% due to the comfort and ease provided by Autopilot systems, particularly on highways and freeways.
Micro and macroeconomic	Multiple	(Fagnant & Kockelman, 2015)	Potential economic savings up to $2000 per AV per year from crash savings, travel time reduction, and fuel efficiency
		(Pettigrew et al., 2018)	Job losses in driving-related occupations but potential job creation in tech-related fields
	Level 5 automation	(Bahrami, 2019)	Potential cost savings from reduced land use for parking and efficient use of urban spaces
		(Faisal et al., 2019)	Increased workforce productivity by allowing passengers to work or engage in productive tasks during their commute, supported by in-vehicle connectivity.
		(Cheng et al., 2020)	Reduction in vehicle ownership by promoting shared mobility solutions.

This section identified the potential benefits of ADS, aiding the stakeholders in defining a sustainable future and letting that guide the policy formation process. Li et al.'s (2019) research guided this approach of investigating technology's potential benefits for policy development in the context of contemporary transportation systems. Backcasting was introduced as a scenario analysis method that involves defining a desired future outcome and then working backwards to identify the steps needed to achieve that outcome. It provided a structured approach to envisioning and achieving long-term objectives, making it a valuable tool for developing ADS policies. By starting with the goal of achieving high standards in all five identified themes and working backwards to identify the necessary steps, the ADS certification process can ensure a structured and goal-oriented pathway. However, as ADS are yet to be deployed on Dutch roads to achieve their potential benefits, the following section defines the need for this research to bridge the gap between the desired state and the current state of ADS certification.

1.4 Research gap

As discussed above, ADS is a complex technology with immense potential for impact. Section 1.1.2 highlights the need to innovate technologies responsibly. The push to embed responsibility within technological innovations, such as ADS, reflects a broader desire to ensure that new technologies serve society rather than disrupt it. Yet, the path from intent to practice is unclear. Certification frameworks fail to address the complexity and ethical considerations intrinsic to ADS, leading to a potential mismatch between technological innovation and regulatory control. This misalignment raises concerns about the responsible deployment of ADS. This research, therefore, intends to

focus on integrating RI practices into developing and deploying ADS in complex urban systems. The following section outlines the scope, sets clear boundaries, and defines the intended outcomes of this research.

1.5 Research scope

The deployment of ADS impacts various stakeholders, often with conflicting values (Santoni De Sio & Mecacci, 2021). While research has aimed to find common ground on ethics and safety standards, as highlighted by Papadimitriou et al. (2022), strategies are still needed to align these differing values within a certification framework. However, certification development is still in its infancy.

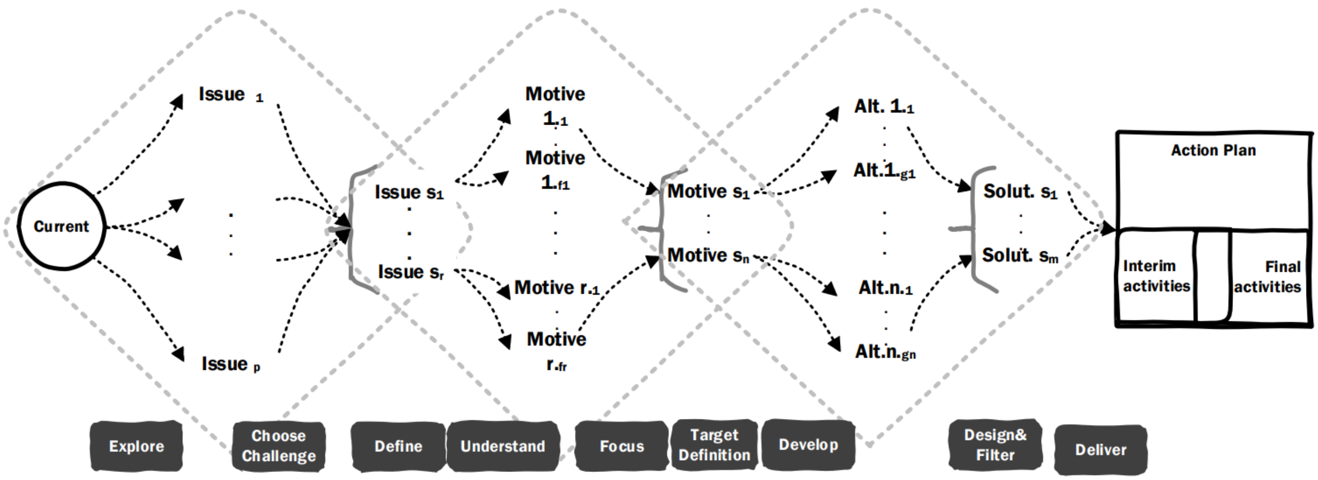

Figure 3: The triple diamond framework (Marin-Garcia et al., 2020)

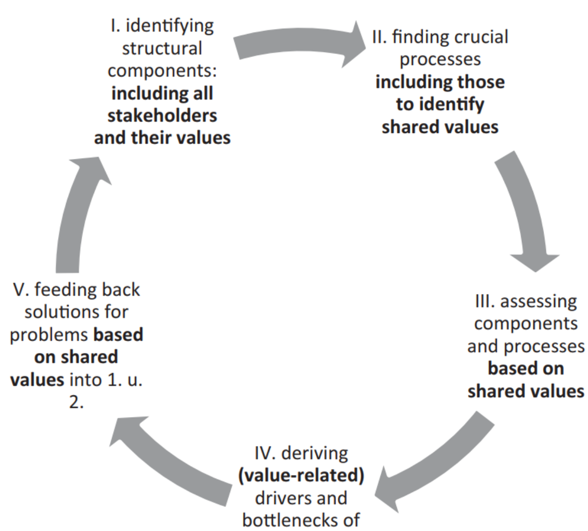

Figure 4 : Werker's (2020) approach to assessing RI.

This research does not dive into finding solutions for certifying ADS responsibly; instead, it **focuses on the initial stage of defining the problems with responsible ADS certification**. Given the complexity of this issue, a structured problem-solving framework, the triple diamond method of Marin-Garcia et al. (2020), was utilised. The focus was on the first two stages of the framework—the "explore/discovery" and "choose challenge" phases, collectively known as the first diamond shown in Figure 3. This stage aimed to identify and prioritise critical challenges and opportunities for further analysis.

Figure 4 outlines Werker's (2020) approach to assessing RI systems, focussing on incorporating responsibility into innovation processes. The second stage emphasises identifying crucial processes that help develop shared values among stakeholders, which aids in ensuring responsible outcomes. The scope of this research is confined to the first two stages of both frameworks, providing a foundation for future studies to explore the subsequent stages.

1.5.1 Meaning of certification

The term "certification" in the context of mobility is diverse because it can refer to multiple processes governed by different authorities, each responsible for distinct aspects of vehicle approval. Multiple regulatory bodies handle different aspects of said certification; for example, the Netherlands vehicle authority and RDW issue type approvals, while other authorities handle operating licences. The legal interpretations of certification can also vary, covering everything from safety compliance to quality assurance, depending on jurisdiction and context. For this research, "certification" is used as an overarching term to focus on broader themes, allowing for deeper exploration in future studies. Building on the identified gaps and the defined scope, the following section formulates the guiding questions for this research.

1.6 Research questions

The research aims to achieve RI in ADS certification on Dutch roads. The scope is to investigate the factors that impede responsible certification and deepen regulators' understanding of the shortcomings in their current certification approach by applying the lens of RI. This approach will assist regulators in identifying critical areas for development, ultimately leading to a certification process rooted in RI. To enhance the regulators' understanding of the necessary steps for aligning ADS regulations with societal values, the following research questions (RQs) are defined

RQ: What are the barriers to responsible ADS certification on Dutch roads?

Sub-RQ1: How does scholarly literature describe barriers to ADS certification?

Sub-RQ2: What barriers to responsible ADS certification on Dutch roads are identified by stakeholders?

Sub-RQ3: How can regulators prioritise the identified barriers and interpret their significance in responsible ADS certification?

This research aims to provide recommendations for improving the roles of various actors and their interactions within the system by answering the main RQ. The research flow diagram in Figure 5 helps the reader understand the research outline.

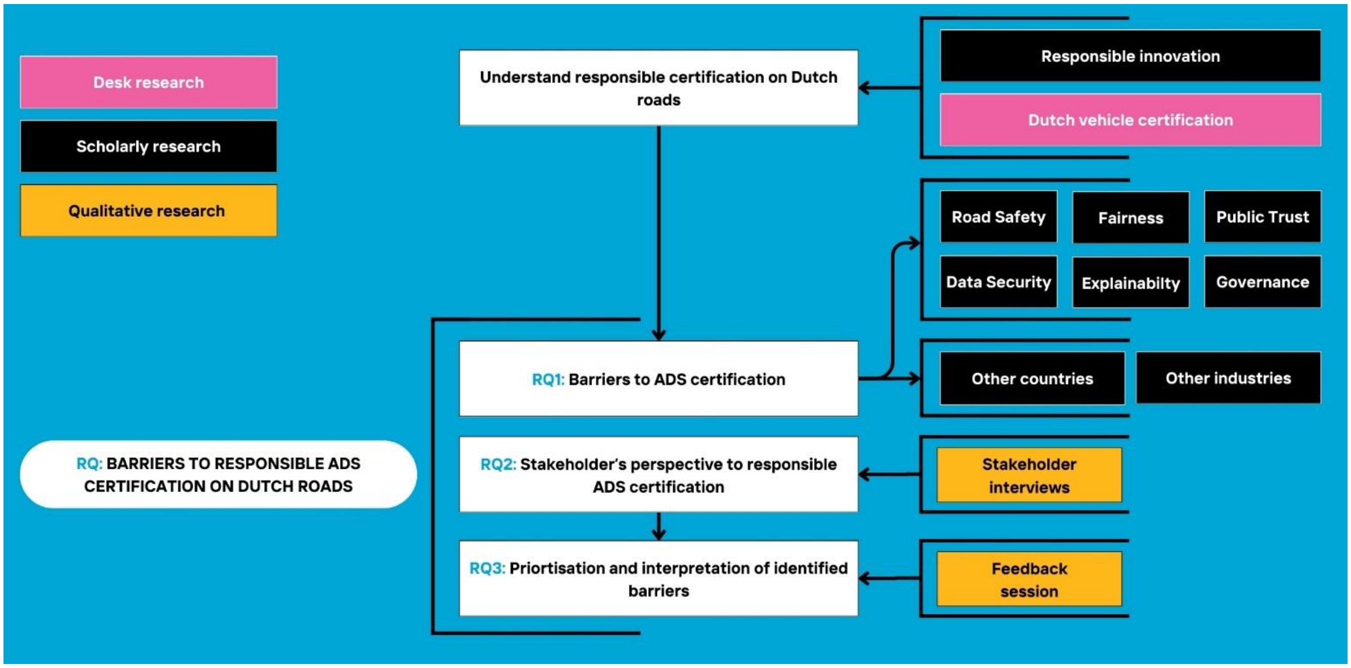

Figure 5: Research flow diagram (Source: Self-compilation)

1.7 Thesis outline

The first sub-research question examines how scholarly literature describes the barriers to ADS certification. As discussed in Chapter 3, this question lays the groundwork for understanding the origins of the identified barriers by providing a theoretical framework for the study and exploring examples from other countries and industries. The second sub-research question investigates the barriers to responsible ADS certification identified by stakeholders. This qualitative analysis, detailed in Chapter 4, focuses on gathering insights from various stakeholders involved in the certification process. The final sub-research topic investigates how regulators prioritise the barriers and understand their relevance in Chapter 5. The discussion in Chapter 6 focuses on improving the pillars of RI and the trade-offs that must be considered to gain consensus, followed by recommendations in Chapter 7. The bibliography and appendices will act as supplements to this thesis.

2. Literature review

The literature review aims to enhance the understanding of the barriers surrounding the adoption of ADS certification. A responsible certification process for ADS on Dutch roads can ensure their safe integration into the transportation system. This section summarises the contemporary scholarly research on issues with ideal implementation and reflections on regulations from other countries and industries facing similar policy-making challenges. It provides an academic foundation for the subsequent chapters and equips the researcher with insights to analyze with a more informed perspective. This chapter aims to answer the Sub-RQ1: How does scholarly literature describe barriers to ADS certification?

2.1 Methodology

The review followed a targeted rather than a systematic approach, focussing on specific themes rather than conducting a comprehensive search of all available literature. This approach was chosen due to time limitations and the need for specialized expertise (Snyder, 2019). Four key papers were used as foundational references, including the Centre for Data Ethics and Innovation (CDEI) United Kingdom (UK)'s responsible innovation framework (2022), which identified seven areas to focus on for ADS certification (Road safety, Data privacy, Fairness, Explainability, Data sharing, Public trust and Governance), and the Council of Europe's 2020 report, which highlighted five values (Transparency, Justice and Fairness, Responsibility, Safety and Security, and Privacy (Altunyaldiz, 2020)). Germany's Act further refined the themes on ADS (Bundesministerium für Digitales und Verkehr, 2021) and insights from California's regulatory experience (Shladover & Nowakowski, 2019a). The initial hypothesis of themes was refined through consultations with the research committee and colleagues who were regulatory officials and industry experts. The final themes included **Safety, Data security, Ethics, Explainability, Public trust, and Governance.**

As an exhaustive literature review was beyond the scope of this research, the focus was on selecting high-quality studies that reflect the barriers to each theme. A hybrid search method was employed, utilising a search string and snowballing technique. Scopus was chosen as the database due to its comprehensive coverage and reliability. The selection process for relevant studies began with a search string. Papers published within the last five years were prioritised, and 10 to 20 papers were shortlisted for each of the six themes for further analysis. Review articles and meta-analyses were favoured to provide a broader perspective over individual studies, forming the foundation of the review. Most of these recent studies contained extensive literature reviews themselves. To further enrich the selection, additional studies were identified by examining the references cited in these initial papers, a method known as backward snowballing. Forward snowballing was also employed to identify scholarly literature that cited initial papers. At this stage, the focus on responsible certification and the Dutch-specific context was intentionally avoided to gather a holistic view.

The search string, consisting of elements presented in Table 2, was applied to article titles, abstracts, and keywords. Elements in the same column were combined using the OR operator, while each theme was combined with an AND operator to the first column. A fuzzy format was applied, where the symbol (*) was used to capture variations of critical terms to ensure the search encompassed all relevant articles. An example query for the theme Safety looked like- ((auto* OR self) AND driving AND (system* OR car* OR vehicle*)) AND (road AND safety OR traffic AND safety). Thirty-four studies used to elaborate on the barriers under each theme are compiled in Table 3.

Table 2: Keywords used for search query

ADS	Themes					
	Safety	Data security	Ethics	Explainability	Public Trust	Governance
(auto* OR Self) AND driving AND (system* OR car* OR vehicle*)	Road safety	Data privacy	Ethic*	Explainability	Public trust	Governance
	Traffic safety	Data sharing	Fairness	XAI	Societal trust	

Table 3: Summary of research focussing on barriers of ADS certification

THEME	AUTHORS	TITLE	YEAR	ADDITIONAL THEMES
SAFETY	Ciuffo, B., Dona, R., Galassi, M.C., Giannotti, W., Sollima, C., Terzuoli, F., Vass, S.	Interpretation of EU Regulation 2022/1426 on the Type Approval of Automated Driving Systems	2024	Data security
	Shladover, S. E., Nowakowski, C.	Regulatory challenges for road vehicle automation: Lessons from the California experience	2019	
	Hansson, S. O., Belin, M.-Å., Lundgren, B.	Self-Driving Vehicles—an Ethical Overview	2021	Ethics
	Sever, T., Contissa, G.	Automated Driving Regulations – Where Are We Now?	2024	
	Hindriks, F., Veluwenkamp, H.	The risks of autonomous machines: from responsibility gaps to control gaps	2023	
	Koopman, P.	A Myth of Safer ADS	2022	
	Ito, Y., Kester, P.	Connected Vehicle Safety Implications	2023	Public trust
DATA SECURITY	Altunyaldiz Z.,	Legal aspects of “autonomous” vehicles	2020	Governance
	Taeihagh, A., Lim, H. S. M.	Governing autonomous vehicles: emerging responses for safety, liability, privacy, cybersecurity, and industry risks	2019	
	Shladover, S. E.	Regulatory challenges for road vehicle automation: Lessons from the California experience	2018	
	Sykam, V. N. K., Mishra, A., Goyal, A., Hicks, D., Nijim, M.	Multi-layered cyber defences in connected systems	2024	

ETHICS	Shi, G., Methocha, V., Atkinson-Palombo, C., Garrick, N.	Sustainable Safety in The Netherlands: Creating a Road Environment where People on Foot and on Bikes are as Safe as People in Cars	2021	
	Ngo, R., Chan, L., Mindermann, S.	The Alignment Problem from a Deep Learning Perspective	2024	
	Cotra, A.	Misalignment in AI Systems: Causes and Consequences	2021	
	Smith, G., Kessler, S., Alstott, J., Mitre, J.	Industry and Government Collaboration on Security Guardrails for AI Systems	2023	
	Jones, R.	AI Safety and Governance Structures: A Comprehensive Overview	2024	
	Singer, P., Tse, Y.	AI ethics: The case for including animals	2022	
	Coulson, G., Bender, A.	Wildlife Mortality and Road Infrastructure	2024	
	Loss, S., Marra, P., Will, T.	Bird–Vehicle Collisions in the United States	2014	
	Awad, E., Dsouza, S., Kim, R., Schulz, J., Henrich, J., Shariff, A., Bonnefon, J.-F., Rahwan, I.	The Moral Machine Experiment	2018	
	Osasona, F., Amoo, O., Atadoga, A., Abrahams, T., Farayola, O., Ayinla, B.	Reviewing the ethical implications of AI in decision-making processes	2024	
	Santoni De Sio, F., Mecacci, G.	Four Responsibility Gaps with Artificial Intelligence	2021	Explainability
EXPLAINABILITY	Shen, Y., Jiang, S., Chen, Y., Driggs Campbell, K.	To Explain or Not to Explain: A Study on the Necessity of Explanations for Autonomous Vehicles	2022	
	Omeiza, D., Webb, H., Jirotka, M., & Kunze, L.	Explanations in Autonomous Driving: A Survey. IEEE Transactions on Intelligent Transportation Systems	2022	
	Atakishiyev, S., Salameh, M., Yao, H., & Goebel, R.	Explainable artificial intelligence for autonomous driving: a comprehensive overview and field guide for future research directions (no. Arxiv:2112.11561)	2023	
PUBLIC TRUST	Dewey, J., Rogers, M. L.	The Public and Its Problems: An Essay in Political Inquiry	2012	
	Kyriakidis, M., Happee, R., de Winter, J. C. F.	Public Opinion on Automated Driving: Results of an International Questionnaire	2015	
	Battel, K., & Pearl, D.	A critical juncture: Promoting responsible innovation in the self-driving automobile sector while improving human factors. Frontiers in Industrial Engineering	2024	
GOVERNANCE	Bertolini, A., Riccaboni, M.	Grounding the case for a European approach to the regulation of automated driving: The technology-selection effect of liability rules	2021	
	NHTSA	Advanced Driver Assistance Systems and Automated Driving Systems: Crash Reporting	2024	
	Hoonsopon, D., Ruenrom, G.	The Impacts of Technological Changes on Product Innovation	2012	
	Bertolini, A., Riccaboni, M.	Grounding the case for a European approach to the regulation of automated driving: The technology-selection effect of liability rules	2021	
	Kubica, M. L.	Autonomous Vehicles and Liability Law	2022	
	Lanzi, M.	Development of Autonomous Vehicles and Criminal Liability issues: Key points	2021	

2.2 Safety

This section will discuss safety-related barriers to ADS certification. The challenges in vehicle certification include not just road safety but traffic safety as well, complicating the certification process. Integrating ADS with current traffic systems is challenging, as traffic-related systems were designed for human drivers with unpredictable behaviour. The certification process requires comprehensive testing to address these complex issues. The analysis will first examine inconsistencies between functional and operational safety standards, where differing metrics and methodologies complicate validation. It will then address the challenges posed by unpredictable human behaviour, system integration, and the added complexities of connected vehicles, which further hinder the path to ADS certification.

2.2.1 Functional and operational safety

Original equipment manufacturers (OEMs[4]) are required to integrate functional and operational safety into every phase of ADS development, yet differing safety metrics and inconsistent accident data complicate this task. Despite regulators setting a benchmark for acceptable risk, many OEMs apply their standards, complicating safety certification. Joint Research Centre's interpretation document (2024) requires OEMs to demonstrate that functional and operational safety are embedded throughout ADS design and development, ensuring vehicles pose no unreasonable risk to occupants or other road users over their operational lifespan. This assessment will compare similar transport services in the given operational domain. The challenge lies in the inconsistency in safety metrics and the difficulty in setting universal acceptance criteria. While the Regulation suggests 10^$^{-7}$ deaths per operation hour as a benchmark, manufacturers often rely on different metrics, leading to safety validation and certification discrepancies.

The legislation compels manufacturers to defend their criteria and measurements, especially when utilising different data or methodologies, which can lead to inconsistent interpretations. Data restrictions such as bias in accident data and the need for exact criteria matched to specific use cases and ODD features must be addressed. Manufacturers are responsible for identifying and choosing similar transportation services to assess current risk levels, ensuring their criteria are consistent with accessible safety data, which neither regulators nor OEMs are prepared for.

2.2.2 Unpredictability of human behaviour

The challenge lies in ADS safely anticipating unpredictable human behaviour as current technology struggles to replicate human decision-making. Shladover and Nowakowski (2019a) argue that road safety concerns arise from the interaction between ADS and human behaviours. Human drivers often engage in actions like sudden braking or unexpected lane changes, which ADS must accurately anticipate. As they note, the challenge is ensuring that ADS can navigate these behaviours without causing accidents or disruptions. S. O. Hansson et al.'s (2021) study also

[4] In this research, the term OEM will be used interchangeably with Car manufacturers, tier 1,2 suppliers, independent developers, and other related terminologies.

indicates that current ADS technology struggles to match the decision-making capabilities of human drivers, who rely on experience and context. The study highlights the regulatory limitations in assessing the accurate replication of human judgment.

2.2.3 System integration

Traffic safety presents a challenge, particularly in integrating ADS with existing traffic systems for various countries, according to Sever & Contissa (2024). ADS must operate within infrastructure designed for human drivers, including interpreting signals and navigating intersections. As they observe, the complexity increases when ADS must share the road with non-automated vehicles and pedestrians. Hindriks & Veluwenkamp (2023) argue that current testing environments fail to replicate road network complexity. Certifying ADS without comprehensive validation could introduce risks, such as misinterpreting or failing to yield, leading to accidents.

2.2.4 ADS safety claims

According to Koopman (2022), the assumption that ADS ensures safety compared to human drivers is more mythical than reality. OEMs assert that their systems are safer than human drivers but are frequently based on limited data and overly optimistic projections. With their common sense and flexibility, human drivers outperform ADS systems in situations where machine learning models fail, notably with infrequent, high-impact incidents. OEMs frequently highlight reduced crash rates in controlled settings but neglect to consider real-world situations. A trust deficit results from this discrepancy between stated intentions and actual behaviour. The lack of transparency in reporting safety incidents and the limitations of their data further erode public trust, requiring more than just rhetoric to build trust; it demands transparency and accountability.

2.2.5 Connected vehicles

Vehicle accident investigations become even more complicated when ADS are connected. Due to their high levels of connectedness with other cars, the infrastructure, and external systems, these vehicles are more vulnerable to technical difficulties and cyberattacks (Ito & Kester, 2023a). Accident investigators must consider these elements and develop new skill sets and approaches like network analysis and cybersecurity.

In conclusion, this section summarises the literature on barriers affecting the safety aspect of ADS certification. The unpredictability of human behaviour remains challenging as ADS struggles to anticipate human actions. Discrepancies in ADS safety claims, often based on limited data, complicate the certification process and trust. Vulnerabilities in connected vehicles, including susceptibility to technical failures and cyberattacks, add further complexity to safety validation. These barriers highlight the challenges in achieving reliable certification for ADS.

2.3 Data security

ADS require extensive data collection to function, which introduces privacy and cybersecurity concerns and concerns about the monitoring capacity. This section explores issues with data security challenges, focusing on scenario-based safety assessments and cybersecurity risks. It first explores the importance of defining the Operational Design Domain (ODD) for safety testing in various driving scenarios. It then examines how ADS rely on extensive data collection to connect with other vehicles (V2V), infrastructure (V2I), and the environment (V2X) for optimal performance, raising issues around privacy and data protection, especially in accidents. Lastly, it addresses the cybersecurity risks of interconnected systems and the need for robust regulations and adaptive security strategies to mitigate potential threats.

2.3.1 ODD: Scenario Generation and Coverage

This paragraph explores the importance of defining an ADS's ODD and using scenario-based testing to ensure the system's safety across various driving conditions, including edge cases and critical interactions. According to the Joint Research Centre's interpretation document (2024), for an ADS to be certified, it must be operated safely within a specific ODD defined by the manufacturers and respond to ODD boundaries. The characteristics of the ODD, such as road types and junction signalling, determine the ADS's required competencies, emphasizing the importance of using appropriate taxonomies, such as those provided by standards to guide ODD definition, which determines scenario generation for testing for the authorities.

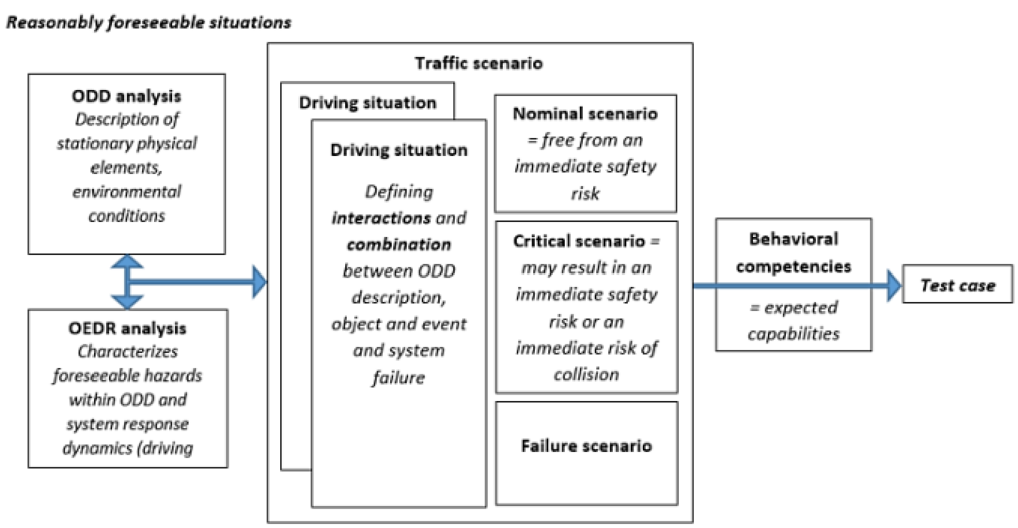

Figure 6: Process diagram for test-scenario generation (European Commission. Joint Research Centre., 2024)

This scenario-based assessment allows authorities to evaluate ADS in various driving scenarios, including critical interactions with law enforcement officers, priority vehicles, and potentially high-severity situations. By considering edge cases and a wide range of foreseeable conditions, authorities can ensure that ADS can handle challenging scenarios. By integrating risk analysis with scenario development, authorities try to cover all potential risks combined with system safety refinement over time. Figure 6 presents the process diagram for the scenario-based approach, which integrates all foreseeable situations to establish ideal test scenarios.

2.3.2 Privacy concerns in ADS

This paragraph addresses the privacy concerns associated with the extensive data collection required for ADS functionality, including V2I and V2X. ADS rely on comprehensive data collection to operate effectively. This data includes personal information and driving details, such as time, location, speed, and the behaviour of surrounding vehicles. According to the conclusions of Altunyaldiz (2020), ADS would connect with other vehicles (V2V), infrastructure (V2I), and the environment (V2X) to optimise performance. Protecting these data nests requires clear data storage and access regulations. These regulations are necessary to address privacy concerns, which are heightened in cases of accidents where sensitive data may be involved.

Regulations have been put in place to control the hazards related to AI. For instance, the EU Artificial Intelligence Act (2023) divides AI systems into risk categories, including ADS in high risk. The findings state that high-risk systems need to operate consistently throughout their lifetime. To guarantee that these technologies can be monitored while in use, the legislation also calls for human oversight, which raises privacy concerns.

2.3.3 Cybersecurity risks

This paragraph highlights the cybersecurity challenges of ADS, stemming from its reliance on interconnected technologies and extensive data collection. The complexity of these networks increases vulnerability, requiring stronger regulations. These systems are vulnerable to hacking, leading to data theft or physical harm, as highlighted by Taeihagh and Lim (2019). The complexity of ADS networks, which include connections like communication explained earlier, increases the risk of breaches. Regulatory measures need to be developed to mitigate these risks, emphasizing the need for robust safeguards and user awareness programmes to reduce the impact of cybersecurity threats on these systems. Shladover (2018) further asserts that higher levels of automation, with the interconnected nature of systems involving wireless communication links, complicates securing them against potential attacks. According to (Sykam et al., 2024), the integration of multiple interconnected technologies creates a layered security environment where attacks can mimic or trigger failures, making it difficult for traditional detection methods to identify and respond to threats accurately. This complexity necessitates the development of advanced incident response strategies that can dynamically adapt to evolving threats while maintaining system integrity and safety.

In conclusion, this section summarises the key barriers affecting data security in ADS certification. Privacy concerns, especially in accidents, and cybersecurity vulnerabilities from interconnected systems pose significant risks. Stronger regulations, risk analysis in testing, and adaptive security strategies are needed to address these challenges.

2.4 Fairness

A comprehensive approach is needed to align AI operations with human values and capacities as AI systems increasingly influence critical decisions. This section summarises the ethical challenges in ADS certification, including responsibility gaps created by AI's opacity and unpredictability and the trade-offs between prioritising safety and balancing other factors such as economic efficiency and speed.

Traditional ethical frameworks, which rely on clear lines of control and intent, struggle to meet the complications created by AI's opacity, unpredictability, and autonomous decision-making skills (Osasona et al., 2024). This disconnect creates what are known as "responsibility gaps," where it becomes unclear who is accountable when AI systems cause harm or fail to act as expected. Responsibility gaps can be categorised into four types: culpability gaps, moral accountability gaps, public accountability gaps, and active responsibility gaps (Santoni De Sio & Mecacci, 2021). Each gap is linked to specific technical, organisational, legal, ethical, and societal factors. Thus, technical and legal solutions alone are insufficient to address responsibility gaps, but a comprehensive approach is needed to effectively address these challenges by combining technical transparency, organisational responsibility, legal clarity, ethical guidelines, and societal considerations.

Hansson et al. (2021) go beyond the generally publicised crash scenarios to look at broader social and political tensions, public safety concerns, and the trade-offs between safety and other needs. Emphasis is placed on the changing responsibility for road safety. As ADS advances, the driver's role reduces, prompting issues about who is responsible for accidents: manufacturers, road system management, or the AI systems themselves. Clarity in responsibility dynamics is necessary to distinguish between task responsibility (obligations to ensure safety) and blame responsibility (accountability for failures). The authors determine the importance of adopting a "Safe System" approach, especially with ADS, due to its potential to impact Vision Zero's ambition. The Dutch dedication to Vision Zero is evident with the adoption of self-explaining and forgiving roads, highlighting their sustainable safety approach designed to direct user behaviour while minimizing collision consequences naturally (Shi et al., 2021). Dutch also perform better than most EU countries in terms of general risk in traffic owing to stringent road safety policies, including lower speed limits on rural roads, mandatory use of seatbelts, and rigorous standards for child restraints and motorcycle helmets (Schoeters, 2023). This directly affects the approach of Dutch regulators in trade-offs between safety and other criteria, such as speed and economic efficiency, illustrating the ethical problems with putting safety first over convenience and financial rewards. The tradeoffs are further analysed in 5.2. The following section discusses the challenges of AI safety and alignment in ADS, then explores the ethical implications for animal safety, an often overlooked aspect of ADS certification.

2.4.1 ADS Alignment

The move from traditional programming to neural network-based decision-making in ADS has raised several issues that need attention in the certification process. This section discusses the literature on AI safety and alignment challenges in ADS. As systems now mimic human cognition, concerns arise about the unpredictability and opacity of neural networks. The literature stresses that AI safety and alignment must be central to ADS policy to ensure responsible development and deployment. Understanding AI safety and AI alignment are the backbones of ADS policy formation because they provide a framework to ensure that AI systems are developed and deployed responsibly, mitigating risks and maximizing benefits. AI safety calls for governance structures to prevent careless or harmful development and strengthen system resilience against risks like cyberattacks. (Jones, 2024). AI alignment, a subset of AI safety, aims to ensure that AI systems perform tasks as intended by their creators. A standard definition specifies alignment as “When I say an AI A is aligned with an operator H, I mean: A is trying to do what H wants it to do.” which means ensuring that AI systems pursue goals that reflect human values or interests (Ngo et al., 2024). Policies based on these principles address potential hazards, uphold ethical standards, and promote accountability and transparency. Misalignment risks, such as developing models prioritising short-term approval over long-term safety, could lead to AI systems making crucial decisions without regard for human values. This underscores the urgent need for policies and techniques to ensure deep learning models are aligned with human goals before they become too powerful (Cotra, 2021).

2.4.2 The case for animal ethics

While much of the literature focuses on neglecting VRUs in ADS certification, Singer and Tse (2022) argue that the ethical impacts on animals are significant yet underexplored in the ADS ethics discourse. Whether driven by humans or AI, cars invariably endanger animals on the road, resulting in injury rather than imminent death, but ADS is supposed to be safer. A recent study shows that every year, an estimated ten million native animals, reptiles, birds, and other species are killed in Australia alone, while other estimates that around 89-340 million birds were killed by automobiles on roadways in the United States each year (Coulson & Bender, 2024; Loss et al., 2014). Various governments, including Article 13 of the Treaty on the Functioning of the European Union, have recognised certain animals as sentient beings, acknowledging their capacity to experience pain and pleasure and thus warranting ethical consideration (Union, 2016, p. 13). MIT Media Lab’s Moral Machine experiment, which gathered responses from 40 million people worldwide to understand public preferences in life-and-death scenarios involving ADS, reveals a strong preference for saving human lives over animals, though cultural variations exist (Awad et al., 2018). These findings underscore the necessity of integrating animal ethics into developing and implementing ADS technologies to ensure a comprehensive approach to AI ethics that encompasses all sentient beings, thereby aligning technological advancements with broader ethical values. The ethical question lies in the role of regulations in addressing and ensuring animal safety.

In conclusion, the section highlights ethical challenges in ADS certification, including responsibility gaps caused by AI unpredictability and ethical trade-offs between safety and economic efficiency. Furthermore, AI safety and alignment ensure ADS systems act responsibly, while misalignment risks and overlooked animal ethics require robust policies to align AI development with broader human and ethical values.

2.5 Explainability

This section summarises the literature on explainability concerns in ADS certification, focusing on the challenges posed by the opaque nature of their decision-making processes. The inability to interpret how ADS reach their conclusions complicates regulatory oversight and hinders trust in these systems, especially in safety-critical situations. Explainability in ADS affects the certification and broad adoption due to the opaque nature of their decision-making processes. ADS commonly rely on complex algorithms, particularly deep learning models, which act as "black boxes" and make judgments without clear, interpretable logic (Shen et al., 2022), (Atakishiyev et al., 2023). This lack of transparency is problematic because it prohibits the whole stakeholder chain, from developers to users, especially regulators, from comprehending how and why the ADS performs in specific ways, particularly in critical safety situations. Without explicit explanations, it is difficult to identify system faults or remove potential biases in a targeted manner. According to Omeiza et al. (2022), the opacity of these systems challenges efforts to guarantee that ADS can make safe and reliable judgments in dynamic, real-world contexts, making explainability a barrier to ADS certification. According to Santoni De Sio & Mecacci (2021), users are more likely to trust and adopt ADS if they can understand the reasoning behind the system's actions.

2.6 Public trust

Public trust needs to be considered in the certification of ADS as per CDEI's (2022) framework, but it is challenging to achieve, as highlighted by the literature discussed in the following section. A clear legal framework is essential for building trust, as it sets expectations and assures the public that certified systems meet specific standards and requirements. However, trust is a complex and challenging concept to define or measure (Dewey & Rogers, 2012). Even though the certification process contributes to trust by ensuring that ADS are safe, there is no definitive way to establish that something is trustworthy. This complexity is reflected in ongoing discussions and debates, where trustworthiness is examined from multiple angles, highlighting the difficulty in creating a universally accepted approach to trust in ADS (Ito & Kester, 2023b). As per Kyriakidis et al.'s (2015b) survey, public trust is not simply gained; it necessitates regular and honest communication from developers and regulators about the safety standards and ethical concerns included in ADS design and operation. The implementation of ADS on public roadways introduces additional hazards, and in the absence of explicit systems for accountability and safety assurances, public cynicism weakens faith in these technologies, according to Battel & Pearl (2024). Trust is discovered to be dependent on other barriers discussed.

2.7 Governance

Addressing ADS certification requires enhancing and adapting governance frameworks to meet specific challenges, such as ensuring accountability and balancing technological advancements with societal norms, as discussed in the following section (CDEI, 2022). This section will navigate governance issues such as liability allocation and the role of anticipatory governance in adapting to ongoing technological advancements. It will also explore how diverse stakeholder opinions must be incorporated into governance frameworks to maintain public trust and ensure accountability in ADS certification.

By setting transparent regulatory standards and confirming that innovative systems function within established legal boundaries, a sustainable foundation for effective regulation can be laid (Hoonsopon & Ruenrom, 2012). According to Bertolini & Riccaboni's (2021a) study, governance systems must handle the emergent issues from ADS, such as reconciling traditional legal categories like "driver" and allocating culpability. The paper contends that a clear and uniform legislative strategy across Europe is required to avoid fragmented standards that might impede the adoption of ADS across various countries. Furthermore, the complexity of ADS lies in multiple stakeholders and necessitates a governance architecture capable of anticipating and incorporating varied public opinions rather than disregarding them as unreasonable or malleable (Forum, 2015). NHTSA's (2024) concept of anticipatory governance introduces the need for reflexivity and adaptability in regulatory measures.

An example is given for governing accident reporting for increased degrees of automation, which must be modified more regularly to keep up with technological advances and worldwide competitiveness. This requirement for adaptation underlines the difficulty of establishing a governance system that provides safety and accountability and is also sensitive to continuing innovations in ADS. The evolving liability issues surrounding ADS are further discussed.

2.7.1 Liability issues

The liability issues surrounding ADS arise as the technology advances and integrates into society. According to Kubica (2022) and other studies, the transition from human-driven to ADS raises complex questions about who should be held responsible in the event of an accident. Some studies argue that manufacturers should bear the brunt of liability, given that the technology and its decision-making algorithms are under their control (Altunyaldiz, 2020). On the other hand, other scholars emphasise the potential role of software developers and data providers, mainly when failures occur due to inaccurate or outdated information (Lanzi, 2021). Legal frameworks are evolving to address these complexities, with different jurisdictions proposing varying approaches to distributing liability between manufacturers, software developers, and vehicle owners. However, as ADS continue to be tested and developed, Bertolini & Riccaboni (2021a) establish that a standardised legal framework is essential to managing liability effectively and ensuring public trust in the technology.

This section concludes that the absence of transparent regulatory standards and limited strategies for engaging multiple stakeholders hinder effective governance in ADS. Evolving legal frameworks are needed to address liability and culpability, along with the changing role of the "driver," while ensuring ongoing accountability in the system.

The first part of the literature summarised the barriers identified in ADS certification across the six identified themes. Safety concerns develop due to conflicting safety metrics, unpredictable human behaviour, and integration with existing traffic systems. OEMs confront challenges in integrating functional safety criteria with real-world settings, which undermines public trust due to concerns about transparency. Regarding data security, ADS demands thorough data collection, including personal information, and mandates clear data storage and privacy restrictions, particularly in accident scenarios. ADS's opaque decision-making processes impede regulatory scrutiny and trust, making explainability an obstacle in the certification process. The ethics of ADS certification highlight responsibility gaps due to AI's opacity, raising questions about accountability in accidents and decision-making. Public trust depends on transparency, clear legal frameworks, and open communication about safety and ethical concerns. Governance challenges include managing liability, incorporating stakeholder perspectives, and adapting regulations to ongoing technological advancements. Addressing these concerns necessitates coordination between OEMs and regulators to establish clear standards and strengthen system safeguards.

2.8 Leveraging global insights

After highlighting the complexities surrounding ADS policies, Li et al. (2019) also highlight the importance of learning from other countries and industries facing similar challenges in ADS policy-making. This section identifies barriers and solutions by exploring successful approaches in different contexts, providing foundational insights for developing effective ADS policies. It begins by examining the railway industry's approach to safety targets, followed by the aerospace sector's use of accountability measures. Finally, it examines military frameworks for ensuring human control over AI systems. These cross-industry learnings offer strategies that could be adapted to enhance ADS certification processes.

2.8.1 Certification lessons from other countries

Different policy approaches emerge in various combinations of social, legal, and political situations in different countries. This section first highlights the lessons from the US approach to ADS governance, focusing on state-level flexibility‘s regulatory challenges. It then explores strategies employed by Germany, Israel, France, and the UK, emphasising that multiple governance models can effectively balance innovation and safety. Table 4 summarises important learnings from each country discussed.

Notably, the EU and the United States of America (US) have adopted distinct approaches to ADS certification, yet both regions stand to benefit from each other's experiences. The EU's focus on system-safety analysis and the US's emphasis on cost-effectiveness reviews present complementary perspectives that can significantly enhance global ADS policies (Fagnant & Kockelman, 2015). Numerous countries are enacting legislation to remain competitive in the evolving ADS market and to encourage the testing and development of these technologies within their borders. This proactive approach aims to foster adaptation in policy-making, enabling learning from countries to leverage global advancements and best practices.

KPMG International’s Autonomous Vehicles Readiness Index (2020) values four pillars essential for deploying ADS- policy and legislation, technology and innovation, infrastructure, and consumer acceptance. Most high-ranked countries had coordinated efforts from the national and local governments while having a single government organization specialising in all aspects of ADS. Collaboration between automotive manufacturers, technology companies, and academia was valued while looking at the supporting technological patents. High-quality roads and extensive EV charging networks were vital alongside digital infrastructure, including 4G/5G coverage and smart traffic management systems. Pilot programmes and real-world testing were considered important in building public trust in 2020, but public rejectance has been growing with cases of unsafe deployment of ADS (Alonso, 2024).

i. The US

Since the beginning, the US has been one of the most progressive National Innovation Systems with the development and deployment of ADS (Meier, 2023). The US currently has no nationwide legal framework for ADS, but individual states decide on special licences according to individual specifications. Corresponding laws exist in 37 US states, with 25 permitting the deployment of complete automation. Alabama, Arkansas and Louisiana specifically limit their ADS laws to commercial motor vehicles, whereas Michigan limits deployment to "on-demand automated motor vehicle networks”(*Advanced Driver Assistance*, 2024).

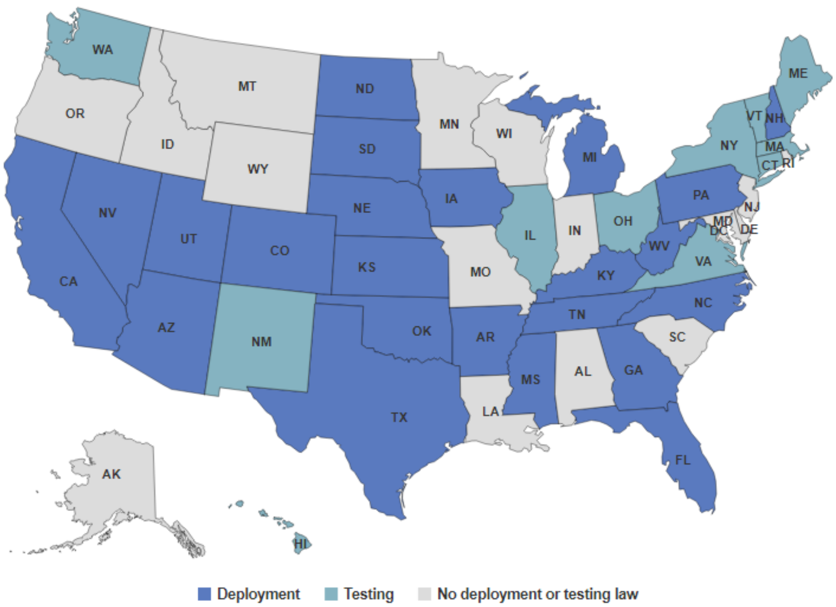

Figure 7: State laws on ADS as of May 2024 (Advanced Driver Assistance, 2024)

As per the summary provided by the Insurance Institute for Highway Safety (2024), states have different operator licensing requirements, mainly a) Requiring licenced operators (30%), b) Conditional licensing (46%), c) No Licenced Operator Required (8%) and d) Not Addressed (16%). States like Arizona and Nebraska require a human ready to intervene until Level 3 is necessary and require them to have a licence. However, a licenced operator is not required in states like Florida and Nevada for Level 4 or 5. And in Mississippi and Oklahoma, “The "automated driving system" is licenced to operate the vehicle. Only six states, including Massachusetts and New York, still require a human operator inside the car at all levels of automation.

Shladover & Nowakowski’s learning from the California experience (2019b) highlights the key considerations: safety certification, public perception of automation risks, and defining acceptable safety levels for ADS. The paper also discusses the need for peer review of driving behavioural competencies and highlights the importance of integrating functional safety and behavioural competency requirements in regulations. Manufacturers must describe their development and testing processes, including closed-course testing and the technical and management methods used to ensure system safety. However, there are no specific requirements on the amount of prior testing or the number of personnel in the vehicle, as these factors were not deemed crucial for safety. A primary focus is the regulations for testing ADS on public roads, prioritising manufacturer responsibility and test driver qualifications. The paper calls for a balanced regulatory approach that fosters innovation while safeguarding public safety. The paper calls for regulation requiring ADS to have advanced self-diagnostic capabilities to monitor their operational status and functionality continuously.

Cruise and Waymo are two of the leading entities of the three permitted in California to deploy driverless vehicles, and can be used as an on-demand ride-hailing service in designated locations, in certain weather and visibility circumstances, time of day, and with specific speed limits (California DMV, 2024). Glaser et al. (2024), based on GM Cruise’s experience of driving hands-free and eyes-on for more than 320 million km, provide data-related legislative recommendations for the government to limit the collection of safety-related data to minimal and crucial elements to prevent burdensome information overload. They advise resisting the urge to incorporate an extensive data collection that might be more appropriate for research rather than regulatory purposes. The paper concludes with design neutrality's importance in fostering the creativity and flexibility needed to advance emerging technologies, particularly in their early stages, which is mainly preventable by not imposing strict design restrictions.

ii. Germany

Germany has set a high standard for regulating ADS, as Altunyaldiz (2020) argued, emphasising the need for regulations to fully respect the right to life. In Germany, ADS regulations mandate that accident-avoidance systems must prioritise human life above all else. The German Ethics Code for Automated and Connected Driving (2017) further underscores this principle by saying that personal injury must take precedence over property damage, and no discrimination based on individual characteristics is allowed. The Parliamentary Assembly of the Council of Europe supports this stance, urging member states to align their regulations with human rights and the rule of law standards, which include respecting privacy and legal certainty (Altunyaldiz, 2020).

One of the key learnings is introducing the "technical supervisor" role, which oversees the vehicle's operations and can intervene if necessary. This addition ensures a human presence in the decision-making loop, enhancing safety and accountability (Gesley, 2021). The legal framework involves a combination of operator, policymakers, and manufacturer liability as they have adapted their legal framework to differentiate between traditional vehicles and ADS. In the event of an accident, liability is assessed case-by-case. If the driver neglects their duty of care, they are liable.

Additionally, the manufacturer could be liable for defects in the vehicle. This balanced liability model ensures victim protection and has proven effective in practice, as discovered by the Horizon 2020, the EC Expert Group to advise on specific ethical issues raised by ADS (2020). For systems that are not fully autonomous, the human-machine interface should indicate who is responsible for control at any given time. Manufacturers and operators must continuously optimise and upgrade automated driving systems, monitoring and improving them when technologically feasible, as liability for damages follows standard product liability principles (Gesley, 2021). The Act of 2021 also defined three key terms- "technical oversight", "risk minimal state," and "accident management" (Kriebitz et al., 2022).

A barrier from US states is resistance to giving regulatory power to federal agencies, fearing a loss of autonomy. A potential solution could be a regulatory sandbox, similar to Germany's model, where states retain some traditional powers but operate under overarching federal standards. This approach allows states to develop testing procedures and adapt regulations to local needs while contributing to a national framework. Feedback from states would help improve national standards, ensuring they are robust and flexible (T. Hainley, 2024).

iii. Israel

In collaboration with the World Economic Forum (2020), Israel's Ministry of Transportation has been redesigning the regulation formation process to fuel innovation. To accommodate rapid technology breakthroughs, policy frameworks must be adaptable and forward-thinking. Multi-stakeholder involvement, which includes industry professionals, academia, and non-profits, should reduce the knowledge gap between regulators and the rapidly evolving ADS world, ensuring that multiple viewpoints and expertise shape the regulatory environment. Dynamic rules offer an adaptable strategy to keep up with technology changes, allowing for safe experimentation and incremental improvements. The Israeli method also emphasises the need for public acceptability and confidence, which may be achieved through transparency measures such as public hearings and polls, ensuring that legislation represents social demands. This proactive strategy involves developing performance indices and risk management recommendations long before full commercialisation, as the Israel Innovation Authority (2020) recommended.

iv. France

France's ADScene programme addresses the challenges of developing a comprehensive scenario database to design, validate, and certify ADS using a secure industrial SaaS platform. This multi-source approach combines real-world driving data, accidentology, and risk analysis to create scenarios, use cases, and test procedures. The platform provides private settings for individual OEMs and a common area for collaborative initiatives, showing France's efforts to improve interoperability and regulatory compliance. (Guyonvarch et al., 2023a).

The methodological report on the safety demonstration of automated road transport systems (2023) presents strategies for crafting driving scenarios, which can be adapted to Dutch regulatory requirements. This report promotes a scenario-based approach by merging various scenario characterization axes to encompass all possible driving situations that ADS may encounter. It introduces a detailed structured layer approach, organising scenarios into distinct layers to ensure thorough coverage of driving situations, hazards, and system responses. These layers include the vehicle's planned manoeuvres, road setup configurations, potential hazards, and the system's reactions to these hazards, ensuring that the ADS is prepared for routine and critical situations. Furthermore, the report considers factors that influence these responses, such as weather conditions and the dynamic behaviour of other road users.

v. UK

The UK recognises ADS's huge potential to revolutionize its economy and society. However, without appropriate precautions, this technology can pose significant hazards. The goal to support a balanced approach that ensures safety while fostering innovation has resulted in them outlining a comprehensive list of emerging processes for safety policies (*Emerging Processes for Frontier AI Safety*, 2023). The following four emerging processes will be essential in ADS policy formation.

The UK's emphasis on independent third-party evaluations and government-industry collaboration, as seen in Red Teaming (Smith et al., 2023), ensures rigorous risk assessments throughout the ADS lifecycle. Comprehensive reporting of incidents fosters transparency, enabling swift identification of safety risks. This reporting approach increases public trust in these technologies. Additionally, adopting vulnerability reporting systems, similar to software bug bounty programmes, allows the public to highlight security flaws. Collaborative research efforts, like Japan's eAI project (Calsi et al., 2023), underscore the importance of investing in safety tools and assessing the social impacts of ADS.

Table 4: Summary of certification lessons from other countries

Country	Major learnings
The US	The decentralised U.S. framework, with state-specific ADS regulations, offers flexibility to meet local needs but risks creating fragmentation in standards. Limiting data collection to essential safety information helps prevent regulatory overload and streamlines safety evaluations. Regulations should require ADS to have advanced self-diagnostic capabilities for continuously monitoring operational status and functionality.
Germany	ADS accident-avoidance systems must prioritise human life and prohibit discrimination based on individual characteristics, ensuring fairness in decision-making. A "technical supervisor" oversees vehicle operations and can intervene when necessary, while the human-machine interface clarifies control responsibilities. The regulatory sandbox approach provides flexibility for adapting local ADS regulations while contributing to a unified national framework.
Israel	Multi-stakeholder involvement, including industry, academia, and non-profits, helps bridge the knowledge gap between regulators and evolving ADS technologies. Public acceptability and trust are prioritised through transparency measures like public hearings and polls to ensure regulations align with societal expectations.
France	Highlights the need for a comprehensive scenario database for ADS design, validation, and certification using a secure SaaS platform. The scenario-based approach ensures coverage of all potential driving situations by merging various scenario axes.
UK	A government-industry collaboration is required for Red Teaming and Threat Assessment to evaluate the performance guardrails of automating human driving instincts and ADS interactions. The reporting structure for vulnerabilities allows outsiders to find safety and security flaws in ADS, which are akin to software's 'bug bounty programmes'.

2.8.2 Lessons from Other Industries

This section examines how regulatory bodies in other industries are confronting similar challenges with the rise of advanced technologies, offering insights into their approaches that could inform ADS governance. It begins by delving into the Common Safety Method-Design Targets used in railways and the fault tree method for safety analysis. It then explores the aerospace industry's use of black box technology for enhancing accountability and transparency in accident investigations. Finally, it addresses the military sector's use of the Socio-Technological Feedback Loop to ensure human control over AI systems, offering a structured approach to AI regulation using RI principles.

i. *Railways*

Filip et al. (2022) conclude that a high-level safety target is needed for ADS. The railway industry is safe and regulated because it uses Common Safety Method-Design Targets for safety requirements. It involves setting specific safety targets, like the maximum allowable frequency of dangerous failures, to ensure these systems are safe for public use. The process begins with system definition followed by risk assessment comprising hazard identification and classification. Risk analysis is then conducted using Codes of Practice (CoP), similar reference systems, and explicit risk estimation. The identified risks are evaluated against risk acceptance criteria to establish necessary safety requirements. Compliance with these safety requirements is demonstrated through testing and validation. Independent assessment ensures that the risk evaluation and management processes are conducted correctly. The procedure is guided by selecting appropriate risk acceptance principles, which help control and harmonize risks to achieve the desired safety levels, ultimately leading to practical measures. The resultant acceptable failure frequencies are displayed in such as 1×10^{-9} per hour for catastrophic accidents involving many people (Class A) and 1×10^{-7} per hour for critical accidents affecting fewer people (Class B), are consensus-driven, ensuring that the safety targets are both realistic and stringent enough to protect public safety. This has been adapted to meet safety standards applicable to ADS, such as ISO 26262.

The fault tree method is a systematic approach used to break down complex systems into smaller components to analyse and allocate safety targets, but it also helps identify and quantify the probability of different failures. The top-level 1×10^{-7} failures per hour target is divided into motion control, planning, and car localization subsystems. Each subsystem is further analysed to assign specific failure probabilities to its components, such as sensors, communications, and GPS. This distributed approach allows regulators to ensure that each subsystem and component of the ADS meet stringent safety standards individually, which should lead to the system's overall safety. For example, motion control, with a failure probability of 5 × 10^-8 failures per hour, encompasses steering and speed regulation systems. Within this category, message corruption in vehicle-to-infrastructure and vehicle-to-vehicle communications, with a failure probability of less than 1×10^{-9} per hour, can lead to incorrect data impacting motion control.

ii. Aerospace

Lanzi (2021) explains that ADS regulation can integrate the concept of black boxes from the aerospace sector to enhance accountability and transparency. Black boxes, critical for recording flight data and cockpit communications, could be adapted for ADS to document the sequence of operational events. This adaptation would address the complexities associated with ADS by providing a reliable means to reconstruct events in the case of accidents. By capturing data such as vehicle speed, control inputs, sensor readings, and communication between the vehicle's systems, black boxes would facilitate a thorough investigation of incidents. This approach not only aids in determining fault but also enhances the development of ADS by identifying and rectifying system failures by building a central accident database. This database will enable the analysis of patterns and causes of accidents, ensuring that the same mistakes are not repeated. By systematically addressing these issues, similar to the US Federal Aviation Administration’s approach to aviation incidents, ADS-related accidents can be significantly reduced over time, improving safety and reliability.

iii. Military

"Operationalization of MHC for Military AI," convened by the Dutch government, shed light on how the military addresses AI regulation and responsible innovation. Elands et al. (2023) propose the Socio-Technological Feedback Loop as a comprehensive methodology to operationalise MHC. This strategy, highlighted in Figure 9, refers to maintaining an ongoing method of designing, regulating, assessing, and adapting human-AI systems at the governance, design, development, and operational levels.

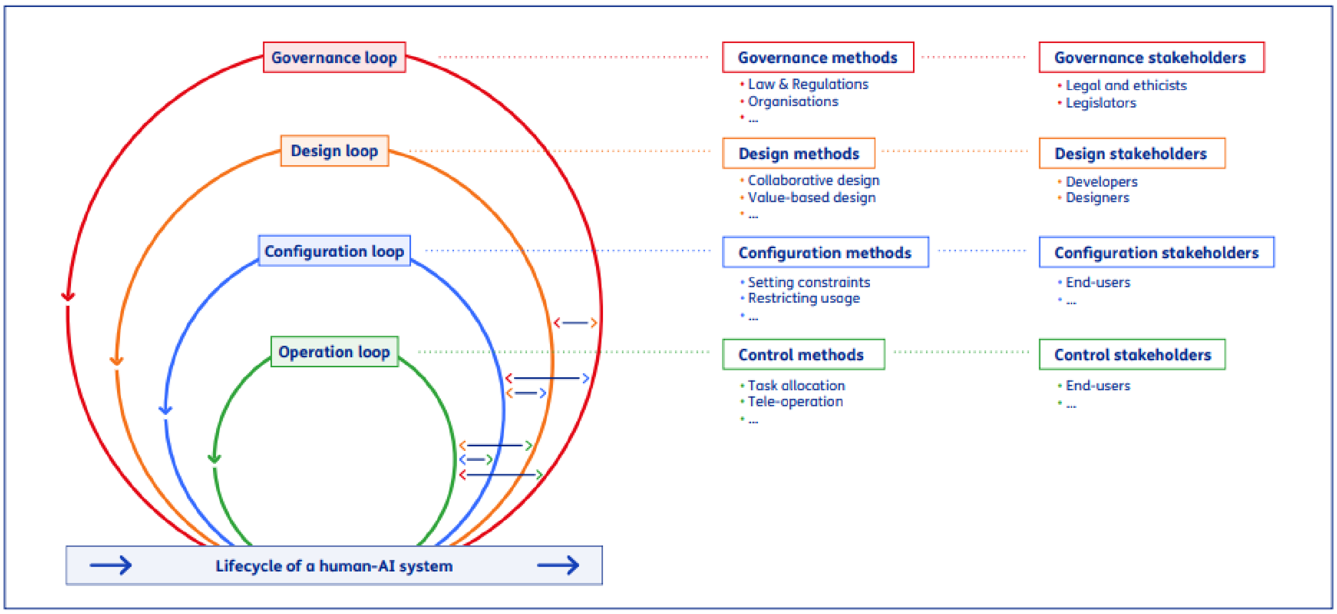

Figure 8: Socio-Technological Feedback Loop for improving human-AI systems (Elands et al., 2023)

The governance loop establishes rules and criteria for AI systems to conform to social values and legal norms, including input from legal experts, lawmakers, and ethicists. Next, the design loop creates the AI system using these rules to ensure ethical and lucrative human-AI interactions. The configuration loop customizes the system for specific settings, whereas the operation loop uses it in real-world circumstances, collecting feedback to modify and improve the system constantly. Feedback from this loop feeds changes to the configuration, design, and governance loops, resulting in a continual improvement process that guarantees MHC is maintained.

Figure 8 explicitly discusses the configuration and design loops, which begin with forming a stakeholder team of relevant experts who examine the possible risks of accidental damage presented by the AI system in each environment. The team establishes mission goals and relevant values, incorporates them into the system's world model, and selects a damage model to guide the AI's conduct. Simulations verify and validate the system's functionality and reduce risks. The AI system is then implemented, with regular tests to ensure MHC is met, resulting in additional changes and continual development. The STFL's iterative and multi-stakeholder approach ensures that AI systems operate under MHC, aligning with mission goals and minimizing unintentional harm.

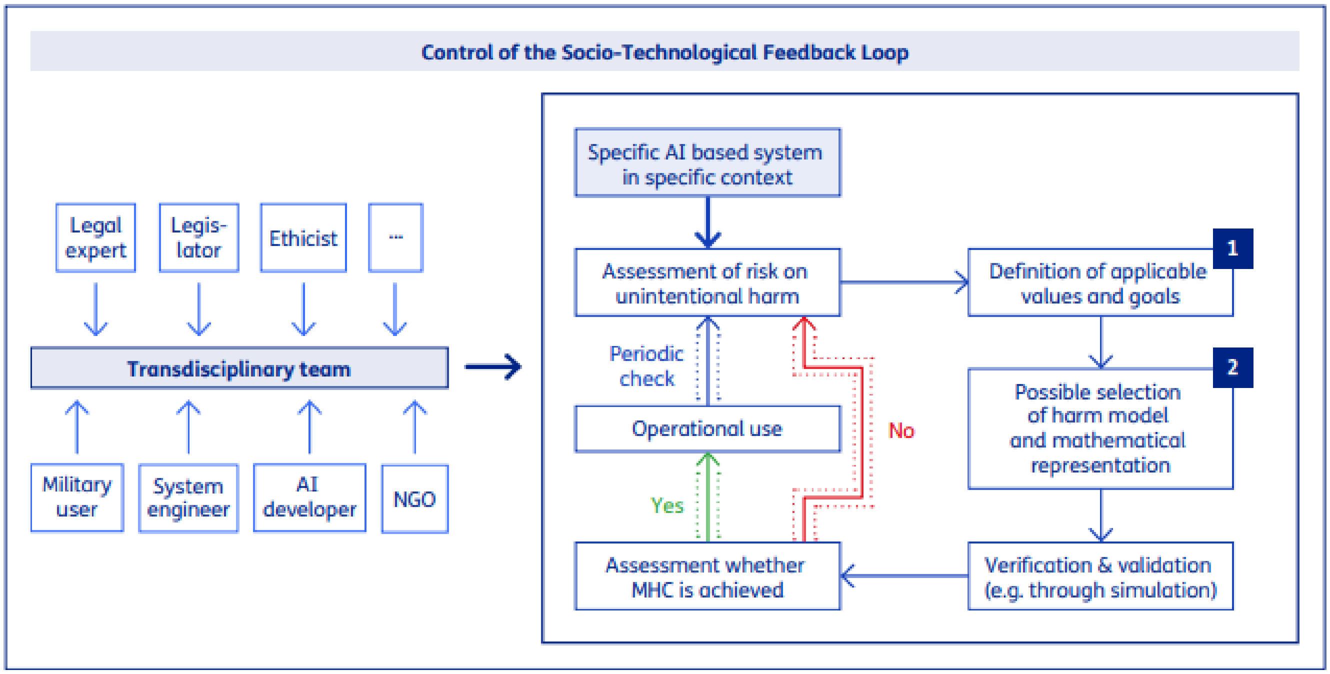

Figure 9: Control of the Socio-Technological Feedback Loop (Elands et al., 2023)

Table 5: Summary of certification lessons from other industries

Industry	Major learnings
Railways	Using High-Level Safety Targets, such as limiting dangerous failure frequencies, ensures rigorous public safety and can inform similar approaches. The fault tree method breaks down complex systems and assigns safety targets to subsystems, aiding in risk analysis and management.
Aerospace	Integrating black box technology from the aerospace industry into ADS can enhance accountability by recording critical operational data during accidents, facilitating detailed investigations and improving system reliability by creating a central accident database.
Military	An Operationalisation method of MHC is the Socio-Technological Feedback Loop, which ensures continuous oversight and adaptation of AI systems by designing, regulating, assessing, and improving them at governance, design, development, and operational levels.

2.9 Summary

This scholarly literature review was divided into two main sections. The first part delved into six key themes identified as barriers: Safety, Data security, Ethics, Explainability, Public trust, and Governance. Regarding safety, the review examined functional and operational safety, the unpredictability of human behaviour, system integration, ADS safety claims, and the complexities of connected vehicles. For data security, it explored issues around ODD scenario generation, privacy concerns in data collection, and cybersecurity risks. Ethics focused on responsibility gaps, the alignment of ADS systems with human values, and the ethical implications of animal safety. Explainability centred on the challenges posed by the opaque decision-making processes of ADS, while public trust was discussed in the context of clear legal frameworks and transparency. Governance examined the evolving role of liability and the need for anticipatory governance to address technological advancements.

The following section focused on learning from different countries and industries, highlighting how they tackle governance challenges posed by emerging technologies to inform ADS's responsible certification process. Table 4 summarised certification lessons from five countries, highlighting diverse strategies tailored to their unique socio-legal contexts. The US emphasises state-level flexibility, while Germany's stringent safety and ethical guidelines, including the role of technical supervisors, set a high standard. Israel’s innovative policy frameworks and France’s comprehensive scenario databases further illustrate the methods to ensure safe and reliable ADS deployment. A regulatory sandbox approach, as seen in Germany, shows promise in addressing rapid technological advancements. Success in the fintech industry suggests that regulatory sandboxes could stimulate investment, regulatory change, and market development in the ADS sector, offering a proactive method to update outdated regulations.

Insights from other industries offer lessons for ADS governance, summarised in Table 5. The railway sector’s use of High-Level Safety Targets and fault tree methods provides a structured approach to managing and mitigating risks by breaking down complex systems into manageable subsystems. The aerospace industry’s black box technology can enhance accountability and transparency in ADS by recording critical operational data for detailed accident investigations. In the military sector, the Socio-Technological Feedback Loop ensures continuous oversight and adaptation of AI systems, maintaining meaningful human control (MHC) at all stages from design to operation.

3. Research methodology

This chapter details the qualitative research approach used to answer Sub-RQs 2 and 3. Semi-structured interviews were conducted with experts selected through a targeted sampling strategy to gather diverse insights. The grounded theory approach was applied for data analysis, using open, axial, and selective coding to identify key themes. A feedback session with experts further refined these findings, leading to the development of a complexity-severity scale. This chapter sets the stage for how the RQ was addressed in subsequent chapters.

3.1 Qualitative research approach

Qualitative interviews serve as a powerful tool to explore the rich and complex narratives that involve human experiences, as per Nathan et al. (2019). This research's choice of conducting semi-structured interviews was grounded in the method's flexibility to accommodate the complex and evolving nature of the ADS. This approach's significance was in gathering insights from experts with different levels of technical knowledge and ethical considerations in the certification process. The interviews aimed to capture each stakeholder's view on responsible certification and identify the obstacles to achieving RI standards. These identified barriers are further discussed in the coming chapters. This section outlines the data collection process, detailing how participants were recruited through a targeted sampling strategy and then interviewed using a structured protocol to gather insights.

3.1.1 Sampling strategy

The research's sampling approach involved using a theoretical matrix to ensure the involvement of a broad range of stakeholders from the ADS ecosystem. The sample selection was guided by a combination of theoretical and practical factors, including research objectives, study scope, population characteristics and experience, access to contacts, and expert networks. This section outlines how purposive sampling[5] was employed to focus on individuals who represented the organisations that aligned with the target group.

[5] also referred to as judgmental or deliberate sampling, is a non-probability sampling technique where participants are selected based on predefined criteria pertinent to the research objectives.

i. *Target population*

The barrier-lifecycle matrix for ADS certification, shown in Figure 10, was developed to recruit participants from a spectrum of expertise across the complete lifecycle of ADS certification. The matrix later aided the interview protocol as well. The matrix was developed based on six themes identified in Chapter 2 and the certification stages outlined in the CDEI's (2022) framework. The matrix was constructed based on the principles of framework synthesis outlined by Brunton et al. (2020), which instructs the development of a canvas informed by background research and discussions to guide data extraction and synthesis. This primarily deductive approach helped maintain a flexible structure that allowed for incorporating emerging topics.

Themes	Pre-authorisation and trials	Authorisation	Operator Licensing	In-use Regulation	Response and Change
Safety					
Data					
Ethics					
Explainability					
Public Trust					
Governance					

Figure 10: The barrier-lifecycle matrix for ADS certification

The goal was to ensure an even distribution of participants across each theme and stage. For example, participants representing different departments of TAAs, inherently responsible for various stages, were recruited, bringing varied years of experience and levels of hierarchy. Academic researchers contributed insights on ethical decision-making and governance, while participants from European institutions provided perspectives on international collaboration and regulatory harmonisation across global and regional levels. This matrix served as the foundation for recruiting the initial batch of participants. Although it did not encompass all the themes found in the literature, the matrix provided a practical starting point given the research's time constraints. The time-consuming nature of participant recruitment, which began early and ran parallel to the literature review, made the matrix an effective tool for achieving the research objectives.

ii. *Recruitment process*

Out of the 48 individuals contacted, 25 interviews were scheduled, and 21 unique interviews were conducted. The recruitment mail is attached in Appendix B. Participants were sourced primarily from the research committee's network, ensuring access to those with significant influence and expertise. A quasi-snowball sampling method was used, where interviewees may suggest additional experts within their networks. Preference was given to interviewing key figures directly involved in the certification process to minimise convenience sampling bias rather than those more easily accessible. Additionally, relevant potential participants for interviews and feedback were identified and recruited by attending industry events, as detailed in Table 10. These events provided opportunities to engage directly with experts in the field, allowing for the recruitment of multiple participants during these gatherings. Participants were recruited until all six themes were explored and explained, even if not all possible perspectives were exhausted. The sample approach is based on M & Bn (2022), signifying that an adequate sample size was achieved using thematic saturation without the need for exhaustive sampling.

Ethical protocols were followed, with approval from TU Delft's Human Research Ethics Committee, including obtaining informed consent from all participants, which detailed the risks and procedures of the study and is attached in Appendix B. The TU Delft data steward verified the data management plan attached in Appendix A. The research was conducted via hybrid methods, using the MS Teams platform, including summarisation. Throughout the process, experimental data collection was carefully managed and kept distinct from the collection of personal data.

Participants received an email before the interview outlining the research topic and their role in the study, attached in Appendix B. The email emphasised the importance of avoiding deep technical discussions and instead focussing on identifying higher-level system factors. It also requested participants to prioritise three themes from a set of six, which would guide the probing questions during the interview. A delicate balance was maintained between avoiding bias through preconceived researcher notions and establishing the research scope. Table 6 provides an overview of the participants in this study.

Table 6: Participant profiles

Participant ID	Domain of expertise	Geographical focus	Themes of expertise
GMR	Senior manager for vehicle regulations and approvals	Global	Safety, Governance, Public trust
GAR	Senior advisor for vehicle regulations and approvals	Global	Ethics, Safety, Governance
NAP	Senior advisor for type approval policy	Netherlands	Safety, Governance, Data
EMS	Senior manager for scientific research at the EC	EU	Data, Ethics, Explainability
NAR	Testing advisor for vehicle regulations and approvals	Netherlands	Safety, Explainability, Data
NCD	C-suite executive for product developer	Netherlands	Governance, Safety, Public trust
UDA	Director for academic research	United Kingdom	Ethics, Data, Public trust
GDD	Director advanced engineering for product developer	Global	Safety, Explainability, Ethics
GIT	Test inspector for ADS	Global	Safety, Data, Public trust
NAL	Strategic advisor for driver licensing authority	Netherlands	Governance, Safety, Ethics
NAA	Human factors advisor and academic researcher	Netherlands	Ethics, Public trust, Governance
EIN	Inspector for Euro NCAP	EU	Safety, Data, Governance
UPA	Assistant professor for human Factors, psychology & ergonomics	United Kingdom	Public trust, Ethics, Explainability
EAR	Senior advisor for vehicle regulation development	EU	Safety, Ethics, Governance
NAP2	Senior advisor for type approval policy	Netherlands	Governance, Data, Public trust
NEC	Technical expert for certification & recall	Netherlands	Data, Safety, Governance
NTA	Academic researcher for traffic law	Netherlands	Ethics, Explainability, Public trust

Participant ID	Domain of expertise	Geographical focus	Themes of expertise
NAR	Senior advisor for vehicle regulations and approvals	Netherlands	Safety, Governance, Ethics
NMR	Senior manager for vehicle regulations and approvals	Netherlands	Governance, Data, Safety
NAR2	Senior advisor for vehicle regulations and approvals	Netherlands	Safety, Ethics, Governance
SCI	Industry consultant	United States	Data, Public trust, Explainability
EPA	Professor for intelligent vehicles	EU	Ethics, Data, Public trust
NAR3	Intelligent systems advisor for vehicle regulations and approvals	Netherlands	Safety, Explainability, Ethics

3.1.2 Interview protocol

In socio-technical research, semi-structured interviews are popular as they provide a flexible yet guided approach, allowing the interviewer to explore specific topics while accommodating unexpected insights from participants (Nathan et al., 2019). An interview guide (Appendix C) outlined four RI themes to explore while allowing for spontaneous follow-up questions. Open-ended questions were framed to encourage participants to provide detailed and descriptive responses, allowing for a rich exploration of expert opinions. The initial phase began with collecting stakeholders' relevant professional experience and interpretations of responsible certification to establish values analysed further in 5.1.

Figure 10: The barrier-lifecycle matrix for ADS certification was then introduced to help them understand the information flow of the collected data and outline the different components involved in responsible certification. Participants were asked to highlight three themes of expertise in the interest of time for probing questions. The next phase of the interview focussed on a deep dive into the barriers to each pillar of RI individually, addressing the sub-RQ2. Before answering, an explanation of each pillar and its relevance to the responsible ADS certification was read. This ensured that the interpretation of every interviewee was heightened while ensuring consistency, and a reinforcement technique by the facilitator was used to align the responses with the research's intent.

3.2 The grounded theory approach

The grounded theory approach provides a method for developing theories directly from data, extracting barriers in this research. This data analysis approach is effective in qualitative research on topics with limited existing literature as, unlike other methods that start with a hypothesis, grounded theory begins with data collection, allowing researchers to identify patterns and concepts (Corbin & Strauss, 1990). This section explains the use of open coding to break down data into units, which were then reconnected through axial coding to form categories. These categories, through selective coding, helped derive recommendations to overcome the complexities of responsible ADS certification discussed in the following chapters. The concept involved constant back and forth between stages, and a sample of hierarchy is illustrated in Figure 11; connecting fuzzy text to research questions using an organised methodology. ATLAS.ti[6] was used for data analysis because of its intuitive interface and availability.

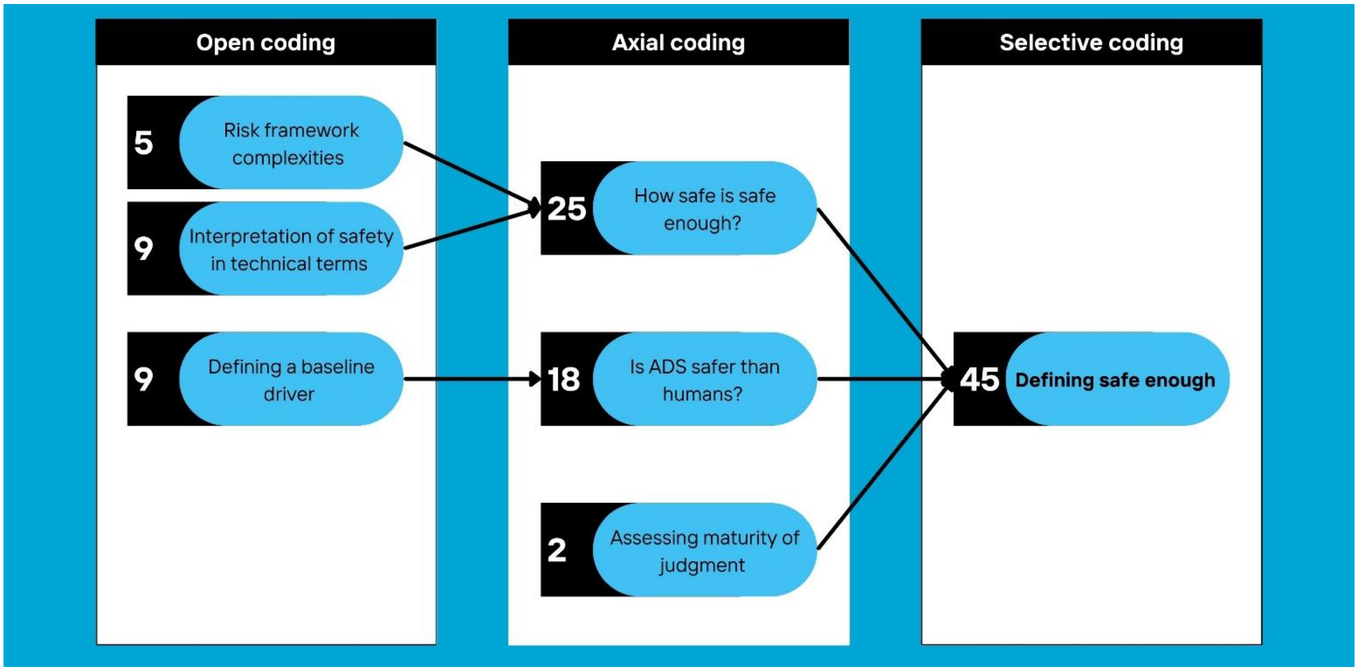

Figure 11: An example of stages of the grounded theory approach

Theoretical sampling in grounded theory involves selecting participants based on emerging data to explore concepts until new information arises (Chun Tie et al., 2019). This study used minimal theoretical sampling as the barrier-lifecycle matrix predetermined the required participants. To avoid bias, the facilitator requested clarification only if a participant's argument corresponded or conflicted with a previous argument. Probing questions were asked based on participants' experience and by tracking themes until data saturation was reached. This system perspective research valued every input provided, and participants were instructed not to do a deep dive to align with the scope.

[6] The software supports qualitative data analysis by facilitating the coding and analysis of complex datasets (*Qualitative Data Analysis Tools for Students & Education*, n.d.).

3.2.1 Open coding

After each interview, transcripts were anonymised, and open coding was applied. Barriers to ADS certification mentioned in the data were identified, and codes were assigned to capture the complexity of the qualitative information. This approach ensured that the data remained organised, facilitating the identification and development of themes (Chun Tie et al., 2019). Each sentence from the 21 transcripts was analysed, with 632 quotations highlighted and linked to one or more codes. For instance, the following quote was coded as “Resistance to change among inspectors”

“Many people (inspectors)[7] are sceptical about new technologies and are not willing to learn or change. This scepticism is a significant challenge.” -NAR

When participants mentioned similar concepts, they were assigned the exact code. For instance, another example from “Resistance to change among inspectors”-

“..[8] in this working field, especially when it comes to vehicles, inspectors or technicians are not very accustomed to coping with changes.” - Anonymous[9]

Groundedness of codes refers to the frequency with which specific codes appear within the dataset (Corbin & Strauss, 1990). For example, the code “Resistance to change among inspectors” would currently be at Groundedness of 2. Groundedness, although a comparative tool, should not be the primary focus in qualitative research, as it can be misleading by suggesting that more frequent themes are inherently more significant (Johannesson & Perjons, 2014). The aim of selecting a qualitative approach was to understand the depth and complexity of the data rather than merely counting occurrences. The goal of this stage was to break down long chunks of quotes into shorter segments, enabling quicker and more effective analysis in the subsequent stages.

3.2.2 Axial coding

Axial codes were produced by merging open codes, which served as overarching themes that connect similar open codes. These axial codes laid the foundation for further stages, which helped understand emergent patterns by investigating similarities between the axial codes. Table 7 explains how the axial code "Inspector challenges" emerged from three open codes. These challenges were grouped to enable targeted strategies for inspectors adapting to data-driven methods, while additional barriers related to open-to-closed norm shifts were excluded to maintain focus on actionable solutions.

[7] Text within brackets has been added for clarity and is not part of the original quote.
[8] The excerpt provided is part of a longer quote and has been included to highlight relevant details.
[9] Might be retracted to prevent identification maybe due to sensitive data

Table 7: An axial code along with its open codes

Axial code with description	Open code	Sample quote	Ground-edness	Participants
Inspector challenges Inspectors are traditionally accustomed to hands-on testing and closed norms and must adapt to new methodologies, including analysing complex data.	Resistance to change among inspectors	"The technical inspectors responsible for approving cars are not willing to learn new tricks. This resistance to change is the most important roadblock. They are accustomed to a certain way of working and are not open to new methods. It's essential for them to be willing to learn and to work together in competence groups." -NAR	6	NAR, NAP2, NAR2
	Increased test inspector responsibility	"That's from being the inspector on one side to becoming more of an auditor and having extensive knowledge of what the possibilities are now that we're going one step further to autonomous vehicles." -GMR	4	GMR, GIT, NAP2
	Increased negotiation to prove compliance	"So it takes a lot of effort on both sides to come to a common point." -GIT	3	GIT

Memos were created in this phase because they allowed the researcher to capture and monitor developing concepts and categories. This aided the documentation of the process throughout the phase as converging and diverging axial codes required going back to interviews to explore initial interpretations and editing open codes accordingly, which was time-intensive. These memos served as reflecting comments that assisted the continual development of axial codes. Table 8 provides an example of the memos highlighting the researcher's evolving interpretation of open and axial codes.

Table 8: Example of memos

Axial code	Memo
Address road user and infrastructure diversity	Merged with "ensure impaired road user safety," "need for inclusiveness," "Address road infrastructure diversity," and "unannounced road repairs." How ADS needs to handle different types of road users and deal with changes in road conditions? People with disabilities should adapt quickly to any changes on the road. *Recommend*- Ensure features meet the needs of all types of road users. Handle every road conditions.
Change traffic rules and infrastructure to adapt	Merged with "Improve road infrastructure". Current technology still can't get signals from the outside world. List changes needed in real-world conditions to better support ADS. Recommend investing in infrastructure quality for safety.

3.2.3 Selective coding

Similar axial codes were combined into higher-order themed codes, providing increased abstraction to help readers grasp the core themes while managing data quantity. Selective codes were refined after discussions in the feedback session. Not all axial codes were merged to retain barriers that offer practical action points, as some addressed unique challenges.

3.3 Feedback session

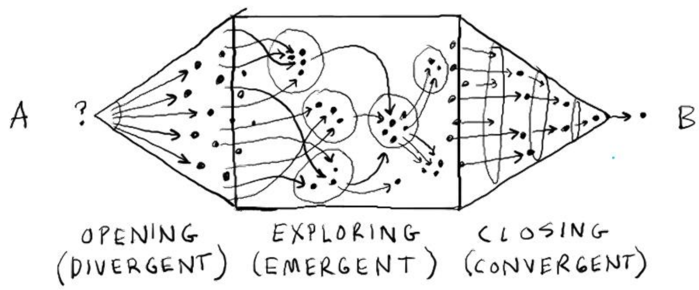

Figure 12: Creative diamond 2.0 (Gray et al., 2010, p. 12)

Five experts, including two newly invited participants, participated in a 90-minute session to identify the most pressing barriers and provide feedback on the researcher's initial interpretation of the interview data. The session was structured around stages two and three of Creative Diamond 2.0, which is used to frame problem-solving processes devised by Heijne & Meer (2019). As illustrated in Figure 12, The method adopts a systematic approach in which ideas are first generated during a diverging phase, as seen in the previously conducted expert interviews, and are later filtered down through subsequent converging stages. To facilitate the emergence stage, the exploring technique of sequencing[10] was employed, which allowed participants to place, group and actively rearrange barriers on a complexity-severity scale. At this research stage, 69 barriers, consisting of axial and selective codes, were transcribed onto cards (see Appendix D for a sample). An anonymised code book was presented to each participant to prevent misinterpretation.

The 'Angels and devil's advocate' technique from Heijne & Meer (2019) was applied for the third stage, also known as acceptance finding. Originating in the roman catholic church, the method fostered balanced decision-making by encouraging participants to explore both optimistic and critical perspectives on an issue, ultimately leading to informed conclusions. A third of the card stack, based on expertise, was distributed to pairs (the facilitator acted as the sixth), and discussions were anonymously transcribed. Each card was placed on the scale sequentially, with participants taking turns playing the role of the devil's advocate to challenge relative positions. The severity spectrum ranges from problems that must be resolved immediately to ideal but not essential. Complexity measures how challenging the problem is, from those requiring significant resources and collaboration to relatively easy-to-address issues.

[10] Sequencing is a problem solving technique for the intermediary stage of the Creative Diamond 2.0 framework, bridges diverging and converging. Involves reevaluating and restructuring available options along one or two axes, sometimes adding a third. Each axis stands for a specific parameter, chosen based on the sequencing goals. This approach helps get a clear picture of all options and see how they relate to the chosen parameters, promoting a shared understanding among members (Heijne & Meer, 2019, p. 162).

The session generated three separate scales and achieved three outcomes- removed miscategorised barriers, consolidated similar barriers that supported the formation of selective codes and helped develop the results by prioritising barriers based on their practical implications. Building on the insights from the interviews and feedback session, the final complexity-severity scale was refined with barriers organised into four quadrants. Each barrier's placement within the quadrant was determined by its groundedness in the data, recognising that a single session cannot fully justify a precise ranking along the scale. The next chapter further explains the complexity-severity scale.

4. Results

This chapter answers the main RQ - **What are the barriers to responsible ADS certification on Dutch roads?** ADS represents a complex socio-technical system where multiple agents interact, inherently raising numerous challenges in developing a process to introduce them responsibly on public roads. The selective, axial, and open codes derived from expert interviews represent the barriers arising from the intertwined social, technical, and regulatory factors that complicate the certification process. Using the research methodology outlined in the previous chapter, 78 open codes were identified and merged into 47 axial codes. 11 selective codes were formed using relevant axial codes to define some themes. The codebook book is listed in Appendix E. 27 Barriers emerged through a careful balance between abstract grouping into broader themes, which could have limited actionable insights or splitting them into more concrete points, risking an overwhelming quantity. Figure 13 compiles all 27 barriers identified in this research, consisting of selective or axial codes. Based on experts' perceptions in the current Dutch context, the barriers were relatively positioned on a complexity-severity scale and divided into four quadrants, as explained in 3.3.

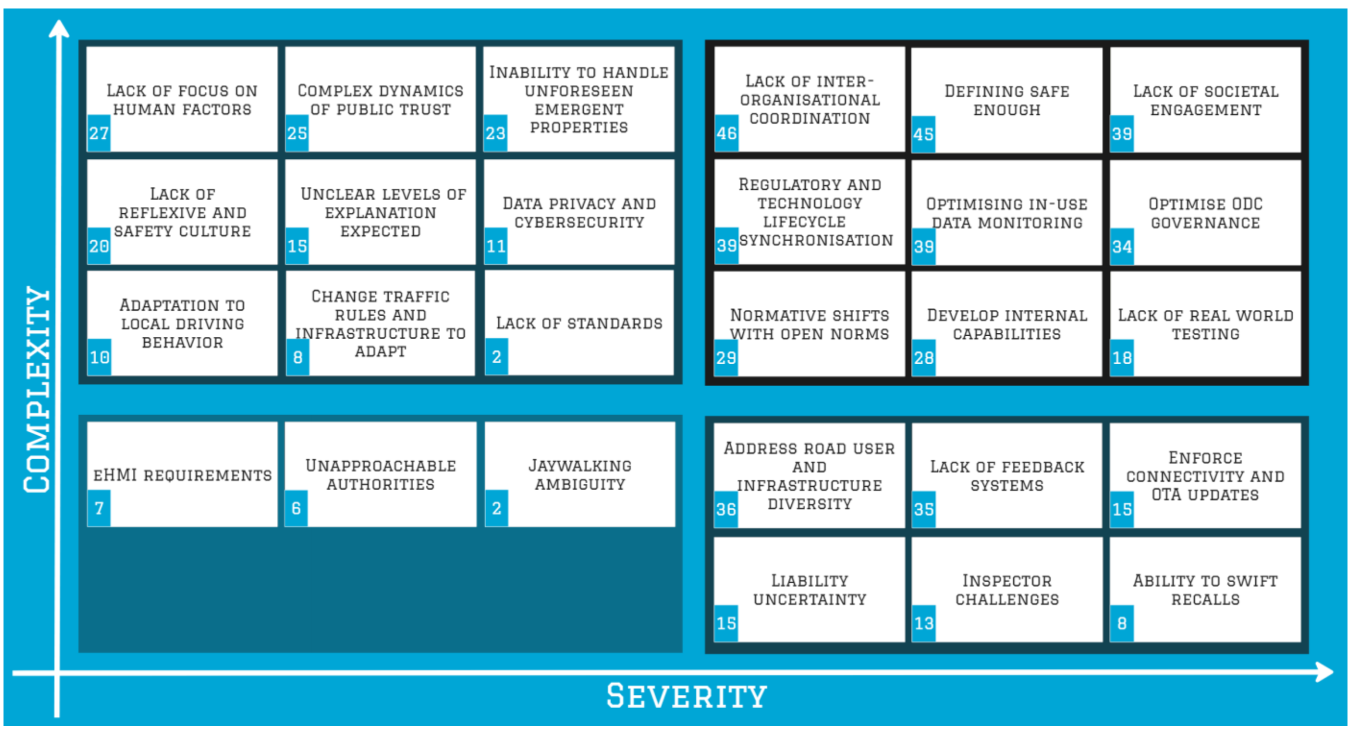

Figure 13: Barriers to responsible ADS certification on Dutch roads

Addressing these barriers requires first identifying and understanding them, and this chapter aims to deepen the reader's understanding of only the most complex and severe quadrant to narrow the research scope, which comprises eight selective and one axial code. Each section provides an in-depth interpretation of expert opinions on critical issues identified, structured around explaining each axial code that forms the selective code. The open codes that shape the axial codes are summarised in the tables at the end of each section. The 27 identified barriers may have strong or weak interrelations and potential causal effects. However, mapping the relations falls outside the scope of this research.

4.1 Lack of inter-organisational coordination

A barrier that surfaced in almost every interview, with participants revealing diverse interpretations of the problem, was bundled in this selective code, a compilation of three axial codes. A lack of coordination among European regulatory bodies, clubbed with unclear divisions of responsibility between national regulatory bodies and a fragmented understanding of ADS at national and international levels, is causing execution delays for Dutch regulators. The axial codes were unanimously placed in the first quadrant during feedback sessions, its severity stemming from being a barrier upon which many other factors rely and the operational inefficiencies stemming from siloed practices. The potential returns of overcoming this barrier are significant, but the risks are equally high, affecting its severity as fragmented approaches drain resources and delay harmonised certification efforts. Experts noted that achieving a unified European framework for ADS approval involves complex negotiations but is necessary for EU-wide type approval, with insufficient research into developing effective coordination strategies.

4.1.1 Lack of European harmonisation

Vehicles type-approved in one MS could be driven throughout the EU, as explained in 1.1.1, but authorities have been unable to create a harmonized ADS approval legislation that supports mutual recognition of vehicle approvals. Each European country is economically and geopolitically different and adapts technological advancements at a different pace, explains NAA. Even though each MS operates under the same legislative umbrella, the resultant fragmentation is significant, as mentioned by GAR.

“What's difficult at the moment is that a lot of different countries have different viewpoints towards the certification process” -UDA

This economic diversity has created inclusivity barriers as some countries aren't even ready or even at the point where they have even thought about ADS and thus can not be included in certification conversations as per NAA. The variability in how European countries approach regulation and certification is another challenge. As noted in the feedback discussion, countries like Germany, the Netherlands, and France each move at their own pace, which affects the overall speed of regulatory harmonisation. This disparity not only complicates the certification process but also poses significant hurdles in aligning thresholds and standards across Europe, further highlighting the need for a more harmonised regulatory framework, outlines EAR.

The absence of a centralised authority akin to those in other industries, such as aviation, is creating a disjointed approach to vehicle safety and innovation, as per EMS. A Euro NCAP inspector pointed out that even the basics of harmonisation of traffic rules are hindered by a lack of regulatory coherence, which poses a barrier to establishing unified standards for vehicle safety and emergency services. NMR underscores the importance of collaboration in areas like cybersecurity, where the sensitivity of information exchange between nations can impact governance and privacy policies at the geopolitical level.

"Someone must take the lead here." -NAR2

4.1.2 Unclear organisational responsibility division

GAR, NAP. GDD, GIT and NAR2 highlighted the confusion surrounding the responsibilities of different entities, including the EU, OEMs, tier-one suppliers, drivers, buyers, insurance companies, type approval authorities, technical services, and regulators. GAR points out that these roles are often flexible and ill-defined, leading to duplicated efforts and disputes over accountability. This ambiguity results in approval delays, inconsistent safety levels, and varying regulatory practices across regions.

“We need to agree on their roles. Sometimes they (organisations) are listeners, sometimes consultants, or they have a big voice.” -NAP

Product developer GDD discussed the interdependency between car manufacturers and road infrastructure in the context of future technologies. An anticipatory certification process should consider both infrastructure and vehicle technologies as interconnected entities. According to NAR2, finding a balance between collaboration and consensus in the Netherlands requires better leadership to set clear long-term goals and a defined course of action, avoiding delays caused by indecision.

Traditionally, the authorities responsible for assessing and licensing human drivers have differed from TAA in the Netherlands. As the task of the human driver evolves with increased vehicle automation, understanding and regulating the interaction between AI systems and human operators becomes imperative. NMR emphasised that this shift requires stakeholders to collaborate to redefine safe driving behaviour standards that encompass human and AI elements.

“… but it remains unclear who will take on the responsibility for assessing AI drivers (ADS).” -NCD

GIT highlighted the need for collaboration among various stakeholders, including traffic monitoring companies, the Ministry of Infrastructure, police databases, and human driver licencing authorities to assess ADS's impact on road safety.

4.1.3 Lack of shared understanding

NAR2 observed that while TAA across Europe faces similar challenges, they are competitive and non-cooperative, resulting in varied enforcement, inconsistencies in standards and fragmented policies that not only increase operational costs for OEMs but also slow down the pace of innovation. The feedback discussion also emphasised the importance of sharing knowledge and experience among certification bodies to educate colleagues and enhance the overall understanding of vehicle architectures and technologies. Further complicating the landscape based on NAR3's expertise is the knowledge gap between technology manufacturers (OEMs and tier twos) and the regulatory environment. Technology providers excel in product development but lack an understanding of the broader legal and regulatory context, while certification inspectors lack the knowledge of the constantly changing technological landscape. Thus, platforms facilitating knowledge transfer are currently missing.

4.2 Defining safe enough

The introduction of ADS has brought to light an underlying ambiguity: how does society define "safe enough" for a new technology? This selective code, consisting of three axial codes, surfaced in sixteen interviews, revealing the issue's intertwined technical and social complexities. While the certification of ADS hinges on both functional and operational safety, there is no consensus on what constitutes adequate safety, and the feedback section highlighted its severity. Defining competent driving in technical terms, especially in unpredictable situations, complicates efforts to regulate ADS, leaving questions about whether ADS should only be allowed if it can outperform human drivers or reduce accidents in the long term.

4.2.1 How safe is safe enough?

As vehicle control shifts from humans to algorithms, the necessity to define acceptable vehicle safety, traditionally concerned with mechanical integrity, must now also include judging the safety of driving decisions made by the software, according to EIN. An academic researcher points out that to responsibly anticipate how vehicles behave, certification processes must adopt a systems approach, encompassing not just the safety of individual components but also the safe driving behaviour of the entire vehicle. The concept of what constitutes "safe enough" driving is elusive and varies widely as per EAL, GAR, and NEC, as discussed above in 4.3.1, due to the varying risk appetite of different national and international organisations. This ambiguity makes setting a clear standard challenging, influenced by varying interpretations of acceptable risk, driving behaviour, and ethical considerations.

"We don't have a clear understanding of what is good, good enough. It comes back to that simple question and it's a simple question, but the answer is very difficult." -NAR

As NAP anticipated, without a universally accepted baseline for what is "safe enough" for each ODD, there might be inclusivity inconsistencies amongst OEMs, widening the economic safety gap. As

EAR pointed out, safety standards are dynamic and change with time in response to societal expectations, political shifts, and technological breakthroughs. They questioned the diminishing returns.

"Eventually, there comes a point where it becomes meaningless to develop further because reaching the new standard is too difficult." -EAR

According to a senior EU official, a conservative European-wide policy ideology highlights that regulators are willing to forgo the deployment of ADS unless these technologies can conclusively meet evolving and stringent safety standards. This dynamic of market pull versus tech push intertwines with their steadfast ideology of not compromising safety, even if it stifles innovation, further discussed in 5.2. Developing and agreeing on a unified solution is complex, as different stakeholders struggle to reconcile their approaches, remarked NAR3, emphasising the importance of alignment on national risk tolerance.

NAL noted that systems, not humans, now exhibit driving behaviour, but defining careful and competent driving remains an open norm. EIN further highlighted the challenge of aligning stakeholders on what constitutes safe driving across varied conditions, while EAR added that safety is context-dependent and not reducible to simple metrics like lane-change timing. EIN desired the innovation to be as safe as an incumbent system, human drivers in this case, but proving that is not straightforward, as explained in the following axial code.

4.2.2 Is ADS safer than humans?

Driver licensing authority advisor NAL pointed out that a crash involving an ADS is four and a half times more socially unacceptable than one involving a human driver. This raised a barrier for ADS to be as good as the average driver and much safer than an average driver. However, NEC, amongst others, pointed out that defining a baseline driver involves determining what constitutes good human driving behaviour, and the complications associated with that are immense. A testing advisor highlighted that testing programs would need to target tens of millions of miles without fatalities to align with the rate of about a hundred million miles per fatality among human drivers. GMR questioned whose responsibility it was to decide on this standard and pointed out the skewed safety statistics due to the variance in an average car and recent models. Crash statistics also vary significantly with driver age, argued NCD. NAA highlighted that, unlike humans, ADS behaviour cannot be generalised across different situations, further complicating the issue. This contrast in behaviour is further amplified in the following axial code.

4.2.3 Assessing maturity of judgment

Academic expert UPA explained that traditional driver licensing hinges on an assumed level of maturity by a certain age, but ADS lack this developmental milestone. While human drivers might rely on experience and intuition to manage unknown situations, ADS are programmed systems limited by the data they've been trained on. The challenge lies in ensuring that ADS can handle unknown unknowns, entirely novel and unanticipated situations, as per NCD.

"We need safety engineering not just a driver test." -UPA

4.3 Improve societal stakeholders' engagement and education

This selective code was derived from four axial codes, and fifteen participants had issues with the certification process, lacking mechanisms for end-users and VRUs to voice their opinions and concerns. Information about what an ADS can and cannot do, including potential risks, is not communicated either by OEMs or regulators. Experts highlighted the severity of the barriers by noting that the lack of regulatory engagement and public education can potentially increase consumer misuse and compromise safety in the deployment of ADS. The lack of public reports about the capabilities, transparent certification processes, and ongoing explanations of decisions highlighted the complexity of the problem. This absence undermines confidence in ADS and its regulatory oversight, increasing the potential for consumer misuse and compromising safety during deployment.

4.3.1 Lack of mandatory inclusion

Inclusive engagement of all stakeholders affected by the introduction of ADS is essential to achieving responsible certification as per GAR. Industry experts UDA and SCI advocated for a holistic approach that integrated diverse perspectives and was mandated at all critical stages of regulatory discourse.

"No one is taking the community with the whole process." -NAR

A noticeable absence of proactive strategies to engage society hampers the inclusion and alignment of ADS with diverse public values and expectations. Excluding VRUs like pedestrians, cyclists, and motorcyclists from regulatory discussions poses safety and ethical concerns, as these groups face the consequences of ADS failures without having opted into their deployment, added EIN.

The challenge lies in ensuring the inclusion of all relevant parties, including those we may not initially recognise as necessary, such as road authorities, city representatives, and various user Organisations, as highlighted by EMS and GAR. Effective cooperation and co-development are crucial, yet the government, researchers, and market players do not work together effectively, as noted by NCD. This gap exists due to the difficulty in balancing diverse stakeholders' often conflicting interests and perspectives. However, the inclusion should work both ways, per a senior regulator.

"Get involved in projects where people (OEMs) are experimenting." -GMR

4.3.2 Societal awareness and acquaintance

Lack of proactive communication combined with the public's limited awareness of ADS advancements contributes to potential resistance or misuse, as per UDA. NAP2 added that the hesitation to accept new technologies stems from a lack of visible proof of safety and reliability. This might involve setting up dedicated oversight bodies or mechanisms to review and approve updates about ADS before they are deployed widely, as per EIN. NEC and UPA mentioned that regulatory authorities also carry the task of spreading awareness about emerging technologies.

"Someone educate or at least inform the general public that we're still closely monitoring everything. It's (ADS certification) not a done deal. So we're still keeping very much an eye out on how these vehicles perform, and if they're unsafe, we have a lot of safeguard mechanisms." -NEC

In Singapore, efforts have been made to familiarize the public with ADS through initiatives such as autonomous dustbins in urban areas. As per a Dutch vehicle inspector, the ministry should lead acquittance initiatives and must ensure that the public is not only introduced to these technologies but also informed about their safety and functionality.

".. public exposure to autonomous systems helps build trust and understanding." -GMR

Initially, both traditional and ADS will share the road, and this transition period raises questions about how to manage the differing behaviours of these vehicles. Unforeseen issues due to a lack of interaction norms and awareness about the behaviour of new technologies could complicate traffic dynamics, as per GDD. To ensure a smooth integration of ADS into society, a strategic effort to increase public familiarity and understanding is essential and currently missing.

4.3.3 End-user training

Another barrier to assuring safe usage is the lack of mandatory training end users undergo for safe operating practices. Testing inspector NAR shared their advice that further training is required since the current license exams do not adequately educate users to handle the complexities introduced by ADS. OEMs should clearly define and inform end users of ADS's capabilities to ensure operational safety, especially limits. GAR pointed out that when the system necessitates the driver taking control, OEM messaging should be regulated and cannot be wrapped with marketing hoaxes.

"I do see a necessity to have correct messaging and explanation of the risks associated with it." - UDA

4.3.4 Lack of transparent decision-making

Building trust requires public reports that detail decisions and the reasoning behind them. It is essential to communicate that supervision is in place and that the public is informed about all secondary processes, such as data usage, as people value privacy as per UPA. To preserve public trust, the certification process must aim for high technical standards and justify judgments taken during the procedures. This is true even when faults are subsequently discovered, added senior advisor NAP2. SCI also wants to extend transparency principles to OEMs but raises concerns regarding competitive advantages.

"It also involves informing end customers about what they can expect from a type-approved ADS." -NAP2

4.4 Regulatory and technology lifecycle synchronization

Sixteen interviews highlighted that ADS was evolving much faster than regulatory frameworks, emphasising a fundamental misalignment with emerging technologies. This misalignment creates a gap where regulations become outdated quickly, hindering the adoption and deployment of new technologies. This selective code coupled two axial codes, highlighting the bureaucratic processes and the subsequent innovation concerns. Experts explained the severity of this barrier due to its impact on the innovation ecosystem and the complexity caused by institutional inertia.

4.4.1 Lifecycle dynamics of regulation and technology

A Dutch regulatory advisor underscores that regulatory frameworks typically evolve through a slower, more deliberate process influenced by public policy, safety concerns, and bureaucratic inertia. In contrast, innovations like ADS are characterised by rapid evolution, as senior regulator GMR explained. Law researcher NTA attributed this characteristic to the higher consensus requirement in regulatory processes. Inclusivity and anticipation, two of the four core values of responsible innovation, as discussed in 1.1.2, are resource-intensive, requiring extended timelines and introducing a trade-off for regulators, further discussed in 5.2.

"In my 30+ years (of experience), a lot of new disruptive technologies have come together. The agility for change needs to be anticipated better and you have to accept the fact that a lot of things will change at the same time and you will have to react more and be more responsive from a government point of view to go along because otherwise regulation is just too far. It is not anticipating quickly enough to follow the technology." -Anonymous

Even being aware of the lifecycle gap, regulators are not proactive, complained product developers NCD and GDD, academic researchers NAA and NTA, and regulator NAR2. EIN highlights that regulatory practices do not mandate anticipatory exercises, and insufficient industry collaboration leads to regulations lagging behind societal innovation and failing to keep pace with technological advancements. The lack of forward vision among regulators has resulted in a dominance of incumbent firms' opinions in shaping regulations, as researcher UDA explained.

4.4.2 Strictness vs innovation

Strict regulations can inhibit innovation by imposing stringent requirements on incumbent technologies, leaving little room for experimentation. On the contrary, regulations can indeed stimulate innovation by lowering compliance requirements and creating a favourable environment. Innovation and regulation have a complicated and nuanced connection. Strict laws may hinder innovation in some areas but provide a foundation for ethical and sustainable ADS development, as UPA, EMS, and NAP2 noted. American consultant SCI explained how this difference affected ADS innovation, as European companies had to navigate more rigorous safety standards, potentially slowing their development pace. American companies could innovate more rapidly but faced varying safety and consumer protection levels, as discussed in section 2.2.2.

"This creates a contradiction: you have something that can be improved, but you don't pursue it because it won't reach the highest standard. Consequently, potential improvements in traffic safety are ignored, resulting in lost opportunities to enhance safety simply because achieving the best is seen as unattainable." -EAR

A senior Dutch regulator pointed out that if the maturity of OEMs were not sufficiently developed, it would be premature to commence certification, especially in critical areas such as cybersecurity. Contrarily, another Dutch regulator argued that the ethical implications of delaying the deployment of life-saving technologies must be confronted. Every year, delays contribute to the unnecessary loss of approximately 24,000 lives across Europe; a more proactive approach could save thousands. Discussions from the feedback session raised the concern that, although a cautious rollout is prudent, the current pace necessitates acceleration due to the extensive costs and time already invested in ADS. There is a critical need to reevaluate and potentially expedite the certification processes.

"Hard law is very difficult to change, especially if you go to international levels. It can take many, many years. Just in the Netherlands, you can easily count for one to two years to have something relatively easy to be changed to be revised." -NTA

4.5 Optimising in-use data monitoring

This selective code focuses on the shift toward data-intensive monitoring and certification, underscoring the need for enhanced capabilities in managing data. Thirteen participants highlighted that scaling up is resource-intensive and needs to be optimised. The barriers mentioned also align with the forthcoming discussion in 0, as optimising monitoring processes would require a comprehensive understanding of the system and the nuanced complexities involved in monitoring real-time. An operational theme that emerged was the need for regulators to enhance their processes to adapt to these changes, including establishing clear internal and external communication channels to improve the efficiency and effectiveness of the certification process. The challenge to change highlighted the complexities involved in establishing databases and fostering greater transparency. The growing reliance on updates, driven by the connected nature of ADS, underscores the severity of thorough retesting to ensure compliance with safety requirements. With enhanced data-driven certification and monitoring capabilities, stringent surveillance measures can provide a reliable framework to test emerging innovations confidently.

"Relying more on monitoring the fleet can help compensate for the lack of knowledge at the authorities and OEMs." -EMS

4.5.1 Monitoring efficiency

Efficiency is required in certifying and monitoring upcoming data-heavy systems, especially with their continuous updates, per six experts. Current processes lack the capacity and knowledge to handle this growing responsibility, leading to knowledge gaps and potential safety risks, as pointed out by EIN and EMS. Without proper requirements, authorities risk becoming overloaded, as EIN noted, with OEMs gathering significant amounts of data but lacking clarity on what needs to be reported to regulators. GAR argued that constant self-assessment is required to ensure the data collected is relevant and actionable for safety and regulatory purposes.

"And do we know what we are looking for?" -EAR

OEMs will try to exploit loopholes in data collection requirements as per GIT. OEMs might focus on meeting the minimum data quantity standards without ensuring sufficient variability in the data. NCD highlighted the importance of real-time certification and monitoring systems, which adapt based on real-time performance and can also be helpful for recalls. A barrier regulator must overcome while certifying ADS is transparent certification of software safety levels. The consequences of deviating from acceptable levels should be clear to OEMs, as that could affect operations drastically, while GAR suggested a spectrum of measures from complete bans to partially restricted versions if there is a threat to traffic safety.

"What is the safety level that is unacceptable that we say you have to downgrade your software?" -GAR

4.5.2 Near miss and crash database needed

Public databases help identify and analyse risky ADS behaviours and scenarios that could pose dangers, enabling the refinement of ADS algorithms to prevent future incidents. Four experts associate the lack of databases directly impacting responsiveness abilities due to information loss. 2.8.2 explained the benefits of maintaining a centralised database in the aviation industry.

".. otherwise we will never be able to act on certain things for the future. So we need to have a really good system for in-service monitoring." -NAR

"no feedback, no change. This is repeated and repeated. This is unsafe." -NAA

According to NCD, collaboration across law enforcement, TAAs, insurers, OEMs and VRUs is needed to establish information-sharing protocols. Regulators lack the mechanisms to gather input from VRUs and other secondary stakeholders, increasing reliance on OEMs to collect and provide data on edge cases as per NMR. This reliance can hamper inclusivity, and lack of access to information as per EIN is an issue that regulators need to tackle.

"cyclists are not going to come and tell OK, this scenario was not OK or I didn't feel safe in this place. but of course the OEM will have data on cyclists as well." -GIT

Transparency is an essential element of public trust in the Netherlands. During the feedback session, it was pointed out that the black box systems involved in accidents will also affect the adaption of other ADS. Therefore, there must be agreements with OEMs in place as per EIN to ensure that incidents are reported and shared openly, with strict penalties for non-compliance to prevent companies from "keeping accidents under the hood" and compromising public trust. NAR2's concern lies in defining strictly what data should be reported.

"We need to filter this data so that they can make good use of it. We need to consider what situations are tricky and critical in terms of safety, occupant or passenger comfort, and trust of other surrounding cars. It might be that there's no accident, no crash, nothing, but the behaviour of the AV is not safe enough and scares others. This is something that needs to be reported." - NAA

4.5.3 OEM transparency

The proprietary nature of software and the significant investments made by OEMs raise a social barrier to willingness to be transparent, as per NCD. OEMs hesitate to disclose accidents because doing so could negatively impact their market value, as pointed out by a product developer. Another challenge is balancing transparency with manufacturers' trust, according to NAP2. Publicising sensitive information might hinder manufacturers' willingness to share openly. NAA underlined the uncertain criteria for the quantity and type of data that OEMs must record and disclose to authorities. The lack of standardised data standards among OEMs causes discrepancies in data gathering, making it difficult for regulators to properly evaluate and assess vehicle performance and safety. The lack of a shared responsibility model amongst OEMs and regulators will delay approvals as per a test inspector. If the OEM is transparent and shares all relevant information, including internal details on development processes, risks can be reduced collaboratively as per NAR2. By being more transparent, responsibility is distributed.

4.6 Optimise ODC governance

As identified by thirteen participants, this selective code is a compilation of three technically inclined axial codes. Participants highlighted the immaturity of the current scientific research framework needed to develop a streamlined yet thorough certification process. The lack of standard approaches and the absence of mandatory or OEM-initiated system capability descriptions are central challenges. The current approach to testing involves multiple stages, from simulation to real-world scenarios, yet there is no unified set of standards guiding these processes. The complexity of this issue arises from the technical nature of complex interaction, which led to the label of Operational Design Condition (ODC), considered a superset for ODD, driver capabilities, subject vehicle and its environment inspired by Khastgir (2021). The severity of the issue is further compounded by the lack of coordinated research efforts to create harmonized testing protocols, leading to resource inefficiencies and delays in certification. Many participants also emphasised the urgent need for scenario databases to efficiently prioritise and address critical scenarios.

4.6.1 Optimise ODC and scenario testing

The sheer variety of conceivable real-world traffic possibilities is a challenge, explained academic researcher UDA. Current techniques to validate ADS are resource-intensive and cannot manage the volume of deployment required as per NAA. A responsible certification should involve intensive anticipation of the full spectrum of scenarios ADS may encounter on public roads and the system's behaviour upon exposure as per EIN.

"So if you have too many scenarios to test then which ones are concrete? Which ones have to be tested, therefore (in) the first instance you have to be able to demonstrate as a manufacturer, a tester or provider of ADS systems that you've done your due diligence." -UDA

The lack of a uniform approach to testing and validation doesn't ensure that all systems meet the desired safety requirements as per NAA. Of the varying standards, the overarching process generally involves a multi-stage approach, starting with simulations, followed by proving ground tests and concluding with real-world testing on public roads, as explained by GMR. The lack of standardised protocols will result in variability and increased compliance costs, but the varying rigour expected versus resources invested is hindering unification. Conventional testing methods, while thorough in controlled settings, fall short in accounting for the variability with ADS and complexity of real traffic environments, according to NCD.

Although widely used in ADS validation, simulation-based testing often relies on models that do not fully capture the nuances of human behaviour or the intricacies of real-world traffic, as per NAA. A trade-off occurs when transitioning to real-world testing between a randomised selection of critical scenarios versus the certification time. This results in a system requiring increased trust in OEM to have gone through a comprehensive scenario coverage, according to EAR.

4.6.2 ODD Limitations

Relying solely on ODD to define the operational scope of ADS doesn't represent system capabilities as ODD focuses on external conditions like environment and geography but neglects to consider the internal performance limitations, as per GAR. ODD lacks a universally accepted definition, leading to inconsistencies in how it is applied across operationally different ADS, leading to variations in interpretations of what constitutes safe operating conditions as per UDA. UDA also highlighted that the probabilistic ODD factors that define thresholds do not guarantee safe operation, leading to oversimplifying safety requirements, for example, in the case of weather unpredictability. Anticipating edge cases is infeasible, creating a responsibility gap in certification, and requires proactive monitoring and adaptation to unpredictable weather conditions to prevent "crazy accidents," as per EAR.

4.6.3 Need for scenario database

NAP suggests that developing a public scenario database based on input and feedback from stakeholders will ensure that no potential edge case is overlooked in the validation of ADS. This database enables a more efficient and targeted testing process by prioritising the criticality of various scenarios, as per NAA. National-level data collection will also expedite training and allow new product developers to enter the market, as explained by product developer GDD and certification expert NEC.

4.7 Normative shifts with open norms

Conventional norms for vehicle certification were grounded in fixed, well-defined criteria establishing clear benchmarks. To mitigate fixed norms' limitations, ADS prompted a shift in the certification approach to open norms for more adaptable processes, introducing a new set of challenges grouped under this selective code. Fourteen participants shed light on this transition, and unlike fixed norms, open norms emphasise broader safety outcomes, offering flexibility in demonstrating compliance. The trade-off between flexibility and consistency, discussed during the feedback session, underscored the complexity of maintaining uniform standards while emphasising the importance of achieving this balance. This shift addresses the complexity and variability of ADS environments that need greater flexibility to enable rapid technological advancements.

"The good thing about open norms is their flexibility, but the bad thing is they can lead to multiple interpretations."-EMS

4.7.1 Interpretation ambiguity

Open norms in ADS certification create challenges in maintaining consistency in jurisdictions, as per ten conversations. The flexibility in interpretation increases adaptability but can lead to varying assessments and expectations depending on the interpreting stakeholder, opening up the possibility of the same ADS getting certified in one country but not another, as per test inspector GIT. Without standardised interpretation guidelines, regulatory approaches would vary, but

European safety standards must be consistent, as per EC researcher EMS. The lack of shared understanding discussed in 4.1.3 leads to a fragmented understanding of regulatory requirements and a barrier that affects all stakeholders.

4.7.2 Shift to system validation

ADS certification now focuses on the vehicle's interaction with its environment rather than just the vehicle. Understanding and regulating the system dynamics of agents and their interactions, including infrastructure, behavioural aspects, and VRUs, is needed as per EAR. Evaluating the safety of a vehicle's design within this expanded context presents a challenge, as ensuring the entire design's safety goes beyond simple measurements, according to EMS.

"So we started with vehicle safety and now we are in the business of Traffic Safety." -GMR

4.7.3 Reduced reliance on regulation

"The barriers to the decision are that we cannot refer to legislation on the level that we used to." - NAP

OEMs would have to build comprehensive safety cases based on documentation and evidence rather than just passing predefined tests as per NEC. Regulators would have to ensure that vehicles meet broader safety expectations, emphasizing continuous monitoring and real-world performance as per NAR2, which they are not currently experienced with. The emphasis has changed from just obeying the rules to understanding and fulfilling the intent of safety standards as per NAP. This social shift has reduced reliance on traditional regulations for regulators and OEMs.

4.8 Develop internal capabilities

Half of the participants heavily emphasised developing the regulator's capabilities with emerging skills as the building block for anticipating and addressing future challenges. Experts emphasised the importance of developing independent expertise within regulatory bodies rather than relying on external consultants and stressed the long-term value of building institutional knowledge. The severity was highlighted by this capability gap effects on every stage of the certification process, with the complexity further underscored by the second axial code highlighting the challenge of sustaining knowledge communities.

4.8.1 Regulators with emerging skills

Ideally, rapidly evolving technologies demand regulators that are both specialized and adaptable. ADS certification requires more than reviewing OEM documents; it demands independent research and expertise in areas like cybersecurity and AI as per NAP, GIT and NAR. NAR2 emphasised evaluating the current capabilities and adapting to emerging needs as an initial step.

"New responsibilities need new ways of working, meaning new competencies and new knowledge areas. If you do not know what you're talking about, you cannot assess people." -GAR

With the onset of open norms, which have flexible interpretations, auditors capable of conducting thorough audits without understanding the technology is not feasible, especially in the case of safety management systems, as pointed out by NMR. Challenging OEMs' compliance and safety protocols will be challenging if they overload regulators with technical assessments that auditors cannot comprehend in time, feared GIT. NAP's current assessment indicated that all stakeholders responsible for regulations lacked expertise, delaying consensus-related conversations. Each regulator specialises in different aspects of traffic safety and needs to be proactive in anticipating the effects of ADS on their operational area to enable inclusive regulations, which is currently lacking.

"To be anticipative in the certification process, you have to do more than just look at the OEM and scrutinize their documents, but have to make your own research." -GMR

Maintaining internal expertise offers long-term advantages that external consultants cannot match. GAR contrasted that with internal teams that accumulate institutional knowledge, allowing regulations to build on previous experiences by retaining critical information. Internal training programs prepare new workers, align them with desired principles and prepare regulators for innovative systems, moving from a reactive to a proactive approach, according to NMR. SCI discussed that consultants frequently engage with clients with competing interests, including regulators and OEMs, and make suggestions that skew legislation to suit their profit motives. This dynamic may result in the formation of guidelines tailored to a particular OEM's expertise, jeopardising the inclusivity and rigour of safety standards.

"Consultants will not do the job in this case, because consultants usually also don't have the overview of all the processes, they specialise in a certain area." -GDD

4.8.2 Lack of knowledge communities

"Create learning communities to speed up the commercial use of autonomous vehicles." -NCD

Government initiatives foster stakeholder synchronisation. Developing forums that bring together inventors, regulators, and users encourages the flow of ideas and is an effective way to build a shared awareness of the technology, issues, and possibilities. NMR highlighted the lack of attempts to establish or support existing knowledge exchange platforms, making it difficult for knowledge exchange between stakeholders and eventually alienating the regulators from insights on market developments.

4.9 Lack of real-world testing

Currently, ADS cannot be tested on public roads in the Netherlands. This axial code covers eight participants' concerns about the lack of testing in real-world conditions, leaving a gap in stakeholders' understanding of ADS performance across varied and unpredictable environments. The code ranks highly complex because public trust is vulnerable in this context; failures observed during public testing undermine confidence, whereas successful demonstrations substantially enhance it. Without practical testing data, regulatory decisions are made without insights into actual traffic behaviours, resulting in regulations that often fail to address the severity of real-world challenges effectively. The absence of government-led initiatives has led to a regulatory environment that does not guarantee that rules are based on demonstrated outcomes but on theoretical talks, as pointed out by GDD. Specific risks and failures may not be identified without real-world testing until ADS is deployed, increasing the likelihood of accidents, explained NAA. Responsible innovation demands anticipation, and real-world testing is missing a missing piece in a comprehensive risk assessment, as per UDA.

"That is not the responsible way of doing it because we cannot, physically, legally anticipate at the moment." -GAR

NMR and GAR explained the complex dynamics. Insufficient real-world data may lead regulators to impose stricter, costly compliance requirements to mitigate unknown risks, increasing the financial burden on developers. If the public perceives that the regulatory certification is based on inadequate testing, trust in the regulatory processes and technology can be eroded. Regulators may face heightened liability risks if inadequately tested ADS are certified and fail. The uncertified versions of ADS potentially have more risks, and regulators are reluctant to expose public roads to them. Further research into possible solutions for reliably mimicking the real world is required as per NAR.

While digital testing provides a controlled environment, NAR analysed that it cannot replicate all potential real-world scenarios necessary to understand the system's behaviour and potential issues. Substantial investment is needed to develop dedicated test areas, which is realistically only feasible by government-led initiatives as OEMs or research institutes do not have the resources to make realistic replicas as per GDD. These areas must be designed to mimic actual road conditions as closely as possible, ensuring the inclusion of all stakeholder requirements, especially VRUs.

5. Analysis

The regulators want to invest in developing an ADS certification framework; the last chapter helps define an efficient way to do that. This chapter enriches stakeholders' understanding of the broader context around the discovered barriers while shifting the focus to the challenging task of reaching consensus. This aim is to enhance transparency in the research and explore the findings' impact by discussing how stakeholders, who often value different things, can understand their role and better cater their strategies to the values they prioritise. Three shared values—Safety, Legal rigour, and Sustainability—are defined, and their compliance implications are analysed. An inherent decision-making characteristic, trade-offs, are uncovered, and the lack of understanding of the complex interdependencies between the barriers is emphasised as a significant barrier in itself.

5.1 Values

Discussions throughout the research process often hover around one fundamental question, and addressing this can help stakeholders have a structured conversation about certification. Achieving meaningful progress in the ADS certification requires addressing the following: **What should the Netherlands, as a society, aim to optimise in shaping its ADS certification process?** A responsible certification process, particularly in the Dutch context, does not merely involve technical validation but extends to broader societal considerations. Regulators would have to decide on various conflicting values, such as whether the focus should be on long-term safety gains or short-term leadership in innovation. Interviews with stakeholders revealed a divide in how the purpose of certification is interpreted.

To make progress in achieving consensus, the research revisits Werker's (2020) approach introduced in 1.5 to define shared values amongst stakeholders. Different scenarios can emerge depending on this fundamental prioritisation, as socio-technical systems are highly path-dependent (Dam et al., 2013, p. 34). The choices made early on would shape future developments, influencing the trajectory of ADS certification and its broader societal impact. Dutch TAA's current strategy statement and interview discussions helped the research define three shared values- Safety, Legal rigour and Sustainability. Multiple interpretations and synonyms were identified throughout the research, and Table 9 aims to streamline and clarify these varying perspectives for a more unified understanding. Sustainability is a broad topic with varied and conflicting interpretations, synonyms with RI; the intent was to define a holistic approach that integrates long-term environmental and economic viability with current regulatory needs.

Table 9: Interpretations of shared values

Shared value	Interpretations and synonyms
Safety	Road safety, Traffic safety

Legal rigour	Regulatory compliance, Liability clarity, Consistency, Fidelity, Rigour, Strictness
Sustainability	Potential benefits/attractiveness (Secondary tasks, Efficiency, Convenience, Reduced cost), Public trust

The following section highlights the impact of the nine barriers discussed in the previous chapter on the shared value identified, putting into context the severity of these barriers and the importance of overcoming them.

5.1.1 Safety

The Netherlands often sets higher safety benchmarks compared to other countries. Consequently, numerous barriers to maintaining such high safety standards were identified. Figure 14 outlines all the barriers that can hamper the desired safety standards. This section further explores the impact of a subset of barriers on safety.

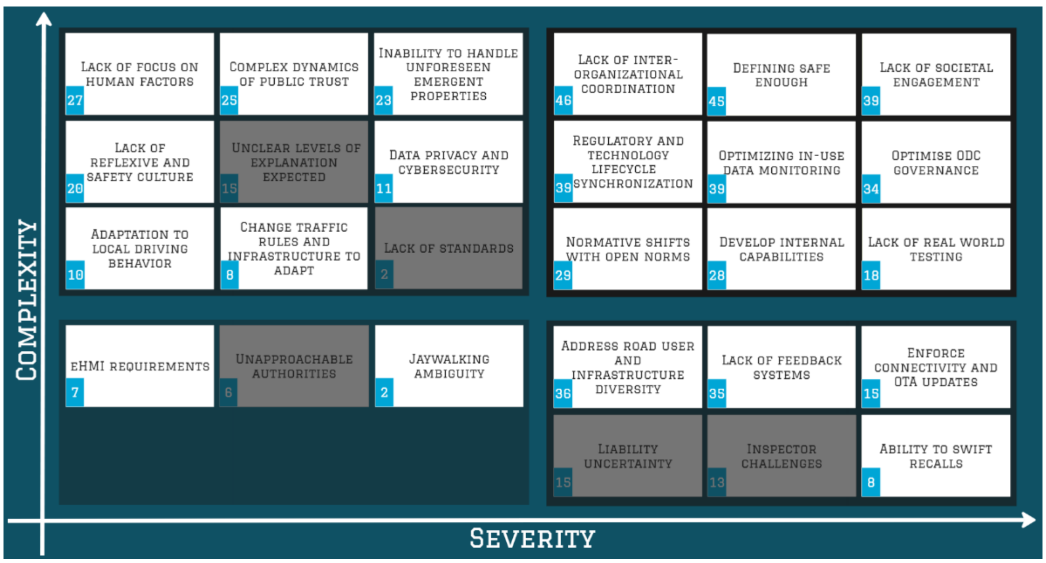

Figure 14: Impact on safety

Current discussions amongst the TAA revolve around aligning the interpretations of open norms. Unlike fixed norms, where any discrepancies can be addressed by adjusting legislation, open norms inherently deviate within certain boundaries. Decentralised interpretations are a consequence of open norms. The lack of European harmonisation has raised scepticism amongst Dutch regulators and consumers about the vehicles entering the EU market from TAAs with lower safety benchmarks. Without cross-European information sharing, the opportunity to learn from regulatory experiences and incidents in other countries is missed. This limits the potential to accelerate safety improvements in the Netherlands.

The shift toward OTA updates demands quick responsiveness. Regulators would take on increasing responsibility for continuous oversight and in-use regulation with ADS. However, the lack of internal skills to optimise processes and address this growing responsibility is concerning. Monitoring capabilities will be significantly hindered without a strengthened internal workforce capable of managing and responding to emerging safety risks.

The gap between the system's intended use and the user's understanding of its capabilities and limitations has been an incumbent barrier intended to be addressed by automotive standards such as ISO 21448 (Safety of the Intended Functionality). Extending to ADS, consumers lack an understanding of complex system functionality, which can lead to dangerous situations. Users might overestimate the system's ability to handle complex driving scenarios, slacking attention mostly by engaging in secondary tasks. Safety is compromised without attempts to bridge this end-user's knowledge gap of when and how to intervene. Assuring safety is challenging without incentives towards system design based on human factors research and end-user training that conveys the system's limits.

The lack of transparency and explainability in ADS systems undermines safety by making it challenging to understand failures. Without open-source, traceable systems, the risks associated with opaque, black-box processes remain unchecked.

5.1.2 Legal rigour

Without well-defined regulations, both developers and users face ambiguity, leading to sluggish ADS development while also hampering adoption. Rapid technological advancements make it challenging for legislation to keep pace, leading to gaps in legal frameworks, which can be caused by multiple barriers, which this research identified in the previous chapter. Figure 15 outlines the key barriers that can hinder the establishment of the desired legal certainty.

The need for clarity about compliance requirements within ADS's multi-layered legal frameworks with differences in priorities across national, European, and international jurisdictions is needed for multinational OEMs to invest and operate confidently. The ambiguity regarding who has the legal authority to intervene after the market introduction of ADS exemplifies regulatory gaps. This shift highlights the need for a clear framework that governs post-market activities and delineates the roles of various authorities, especially TAA and MSA.

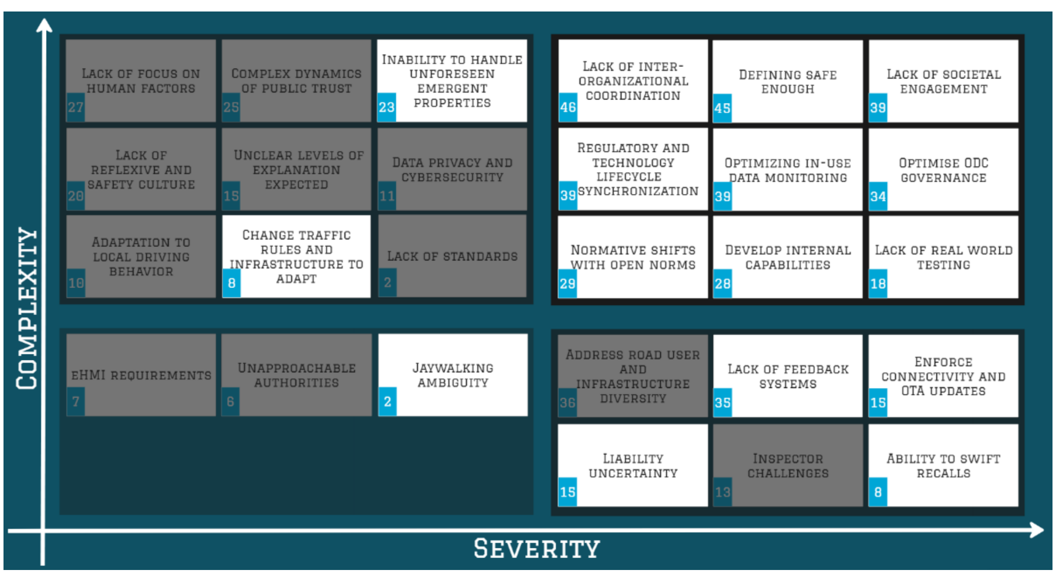

Figure 15: Impact on legal rigour

Rapid revisions to legal norms can increase legal clarity, but they typically come at the sacrifice of legal rigour. The lack of enforceable norms encourages unofficial standards, resulting in legal inconsistency among regions. This scenario presents enforcement issues as authorities attempt to apply archaic legal frameworks to current technologies, reducing the efficacy of legal protection.

Shifting to open norms encourages innovation but introduces many barriers to achieving legal rigour. Open norms are inherently open to interpretation. Achieving legal rigour with open norms is challenging. This raises the question of whether open norms are appropriate if legal rigour is a fundamental goal.

Testing aims to increase trust in ADS, but this will only happen if there is trust in the test procedures. Until clarity for the desired ODC governance approach is laid down, OEMs have a barrier in aligning their development methodologies, increasing the likelihood of legal disputes over liability and compliance.

5.1.3 Sustainability

Sustainability encompasses various meanings, from environmental responsibility and resource efficiency to long-term economic viability and public trust. Achieving potential benefits discovered in 1.3 is essentially fostering sustainable, forward-looking development. Barriers to sustainability often prioritize short-term gains rather than aiming for a long-term approach. Figure 16 highlights key barriers that impact establishing a sustainable certification process.

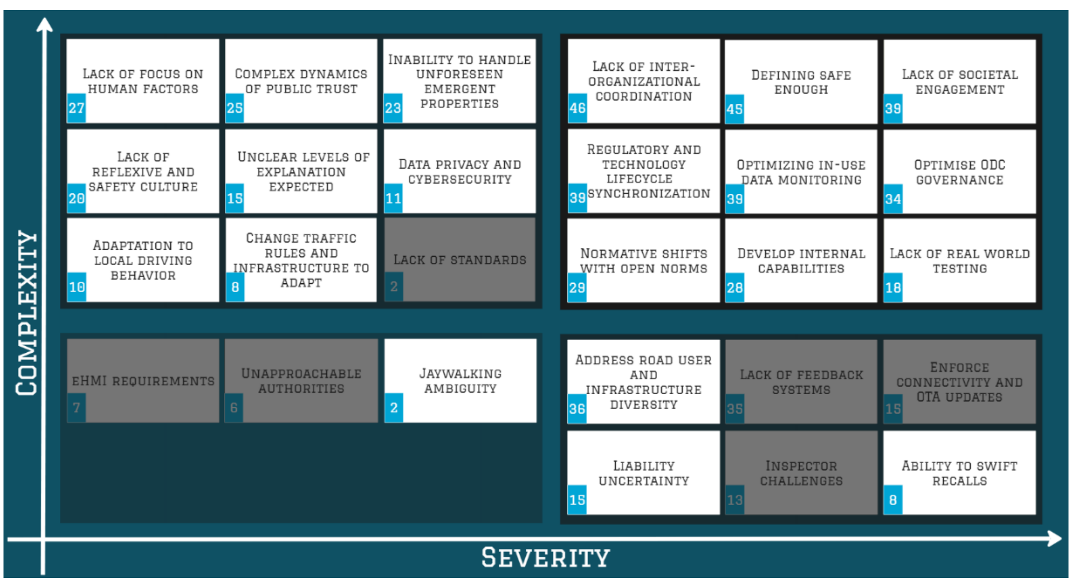

Figure 16: Impact on sustainability

Due to limited scope, regional ADS certification and deployment can initially benefit from rapid, independent research. However, this approach can soon encounter challenges. **Increased compliance costs** emerge for OEMs as each country develops its standards and certification processes, creating a complex regulatory landscape that leads to consumers bearing additional innovation costs. The **high cost-to-convenience ratio** offered by the current ADS is not sustainable for public adoption and is worsened by geographically restricted ODD. The lack of European standardisation hinders long-term sustainability.

Starting from Level 3, ADS requires individuals to perform tasks akin to airline pilots. The task of continuous monitoring and maintaining readiness to intervene at any moment is one at which humans are inherently poor. Drivers lack the expertise or interest to do such complex tasks efficiently, hampering long-term adaption. ADS is replacing easy tasks with more difficult ones, which is counterproductive.

The asynchronous regulatory and technology lifecycle has resulted in higher development expenses and a delayed return on investment. Developers have to constantly adjust to unpredictable and evolving legislation, extending development timelines. Navigating the hype cycles of technology developments, particularly disruptive technologies like ADS requires regulators to balance diligence and responsiveness (Dedehayir & Steinert, 2016).

Open norms in ADS increase development costs due to the need for continuous updates, increased testing, and customisation across jurisdictions, unsustainable for both OEMs and regulators. Compliance with open norms requires navigating uncertainty and higher investment in transparency research potentially delaying market entry.

This discussion highlights the importance of identifying shared values for stakeholder consensus and emphasises the need for an ADS certification framework that prioritises safety, legal rigour, and sustainability.

5.2 Trade-offs

Values outlined in the previous chapter cannot be fully realised within a single framework, meaning that pursuing one may require compromises in achieving the others to some extent. Policymaking is all about trade-offs, and balancing trade-offs has become complex in terms of transport policy. This section aims to understand these complex dynamics of the trade-offs that exist in a web of interconnected factors, each with its own causal impacts and potential outcomes. Responsible certification relies on carefully choosing what competitive factors to focus on and improving them at a balanced rate to achieve a more harmonious approach, as outlined by Akbar et al. (2020). The last section outlined three values for which the certification process aims to optimise. As per Morrison-Saunders & Pope (2013), trade-offs should be evaluated at the start of any development process, and it's important to define clearly what impacts are acceptable and which are not for successful trade-off management. Since ADS certification is still in its infancy, this discussion offers stakeholders insight into the key trade-offs they must navigate to balance identified values.

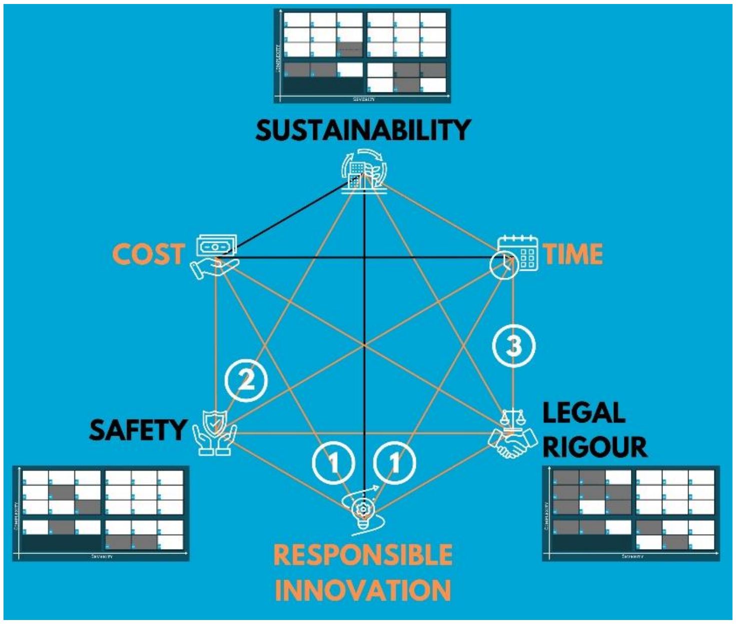

Figure 17: Trade-offs in responsible ADS certification

Process trade-offs represent the realities of decision-making in an imperfect society where resource limitations or cognitive ability hinder decision-makers. Two critical factors in this context are the time and cost invested in developing a certification framework which underpins efficiency. RI is a societal goal guiding these efforts. These factors—time, cost, and RI—combined with the three shared values of safety, legal rigour, and sustainability, form the complex core of the most commonly occurring trade-offs that need to be agreed upon and are visualised in Figure 17. A deep dive into the sensitivity of the trade-off, which refers to the change in one variable resulting from altering the other, will be done for three trade-offs. The orange lines in Figure 17 are the trade-offs discovered from the qualitative research. This doesn't establish an absence of trade-offs for the rest of the factors represented by black lines, for example, the relation between development time and money potentially being inverse to an extent until plateauing due to its dependence on other factors. Other trade-offs were also discovered but not discussed due to a lack of direct relevance to the RQ. They balance positive and negative outcomes when choosing between competing options, often resulting in gains in some areas at the expense of others (Morrison-Saunders & Pope, 2013). For example, regulators need to decide between hiring consultants who may provide immediate specialised knowledge and solutions, which could reduce the long-term development of internal capabilities.

Literature summarised in **Error! Reference source not found.** concluded that Dutch regulators face ethical challenges in balancing safety with speed and economic efficiency, highlighting the trade-offs between prioritising safety and other practical considerations. Legal rigour vs RI was highlighted in 4.4.2 with a trade-off between the regulation's strictness versus an environment suitable for innovation. Strict regulations can hinder innovation by imposing rigid requirements, but when designed with an awareness of their impact, they can also create a favourable environment for innovation, though this balance is currently lacking in the ADS certification. Simulated testing, as explained in 4.6.1, was a trade-off between fidelity and cost, as even after thorough replication, residual uncertainty remains, as also discovered by Koopman (2022). 4.7.1 explained the trade-off between flexibility and consistency, highlighting how the adaptability of open norms in ADS certification can lead to inconsistent interpretations across jurisdictions. Other necessary trade-offs that will occur are discussed below.

5.2.1 RI vs Resources

RI is resource intensive, and responsible certification of ADS will also require higher than usual development time and money (Lubberink et al., 2017). Anticipation involves conducting extensive research and simulations as well as real-world testing, where allocating additional time and funds would enhance the rigour of outcomes. Inclusiveness necessitates collecting input from large groups, such as end-users, which involves organizing extension input collection. Managing diverse perspectives leads to time-consuming negotiations to reach a consensus. Responsiveness is feasible by establishing platforms that rapidly gather and process feedback and maintain readiness for emergencies, which entails developing robust infrastructure and protocols. Reflexive processes demand regulators periodically evaluate their practices, dedicating employee time to review activities and integrate lessons learned, thereby diverting attention from other responsibilities. These resource-intensive processes compel regulators to determine the extent of RI they can support within their available timeframes and budgets. This often requires making deliberate compromises, which must be documented and communicated.

5.2.2 Safety vs Sustainability

Determining the safety of a complex system inherently involves complex trade-offs either due to the simulation time or costs involved with testing kilometres to gain sufficient confidence in the system's reliability. Additionally, the challenge lies in balancing the level of safety required with what is deemed sustainably acceptable, as explored in 4.2.1, while answering "how safe is safe enough". Sustainability in ADS certification hinges on achieving higher public trust and realising the full benefits compared to human drivers, adding layers of complexity to an already intricate dynamic of acceptable system safety. The pressing argument is that the lives currently lost in road accidents, which ADS promise to save, are increasingly seen as the responsibility of regulators, whose delays in introducing these systems contribute to ongoing fatalities, as per GAR.

Safety in ADS extends to data privacy as well. Prioritising data privacy can restrict the collection and sharing of real-time traffic data, essential for optimising traffic management systems—a key potential benefit of ADS (Nastjuk et al., 2020). While safeguarding user privacy addresses lower-risk safety concerns, achieving high levels of data privacy may hinder broader benefits in traffic safety and transport efficiency. This trade-off reflects the tension between maintaining individual privacy and achieving higher-impact outcomes in traffic safety and transport efficiency.

5.2.3 Legal rigour vs. Time

The complexity of liability in ADS, especially in accidents, complicates the certification process. Traditional legal frameworks are not equipped to address the nuances of ADS operations. This uncertainty requires additional legal reviews and potentially redesigning system components to mitigate liability risks, increasing overall development time. Compliance with multiple jurisdictional standards also contributes to these delays (Narayanan et al., 2020). Rushing through the certification process without fully addressing legal concerns could lead to unforeseen complications, undermining public trust and safety. Conversely, prolonged development cycles due to legal uncertainties will stifle innovation.

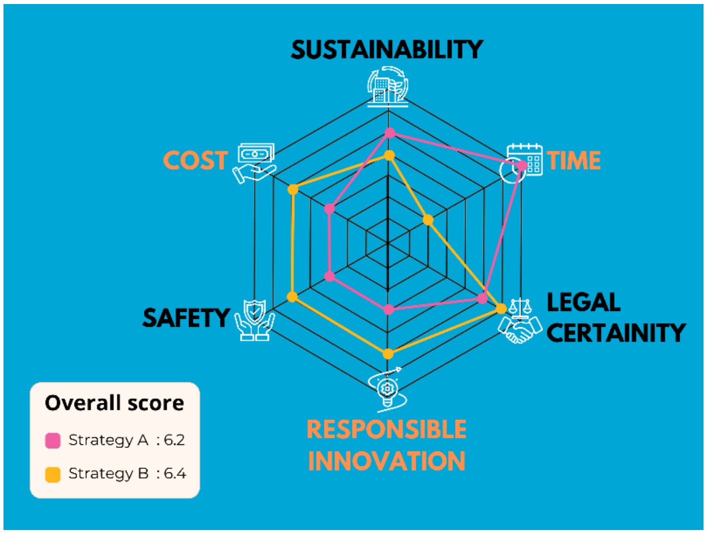

Figure 18: Spider chart for hypothetical strategies

5.2.4 A hypothetical scenario

Two hypothetical certification processes have been devised to understand better the importance of recognising the implications of the trade-offs discussed above. Strategy A represents a quick policy to meet the market push, maintaining legal certainty but neglecting responsible innovation and full safety assurance. It offers a low-cost solution that provides immediate benefits from new technologies but sacrifices thoroughness. Strategy B, in contrast, takes a deliberate approach, ensuring legal certainty and safety at the cost of higher investment and lower sustainability for continuous use.

A preliminary cost-benefit analysis shows that both strategies score similarly on desired metrics, as shown in Figure 18. However, the pathways taken to achieve the end product—and the characteristics of the product itself—are distinct. This highlights the need to define acceptable thresholds for each variable in certification, above or below which the outcomes become unacceptable. Mouter (2020) notes that not all factors in transport policy carry the same weight, a factor that should be carefully considered when adding more variables to perform an in-depth cost-benefit analysis of alternative certification processes. Building on the value-based analysis of the results, the following section adds an additional analytical outlook to ADS certification challenges.

6. Discussions

The four pillars of responsible innovation—anticipation, inclusiveness, responsiveness and reflexivity—serve as the foundation for this research. Each of these pillars defines the theoretical standards for responsible ADS certification, yet multiple barriers identified in the results reveal gaps in meeting these criteria. These barriers hinder the claim that ADS development aligns with RI. The trade-offs analysed in the last chapter show the complexity of managing interrelations between competing priorities. However, RI, as used in that analysis, has its complex interpretation, with each pillar dependent on various barriers identified throughout the research. This chapter focuses on how specific barriers impact each pillar, exploring the implications of failing to meet RI standards. The discussion synthesises the findings of the results, demonstrating that addressing these barriers is key to responsible ADS certification and helping stakeholders prioritise efforts aligned with their vision of an accepted societal future. The section then discusses the scientific relevance of its findings. Additionally, the study acknowledges limitations in interview data, geographic generalisability, sampling, and researcher bias, offering insights into how future research can improve data collection and mitigate these pitfalls.

6.1 Anticipation

An anticipative ADS certification should intend to mitigate the negative externalities of introducing ADS. Multiple barriers prevent the certification process from reaching its full anticipative capabilities. This section discusses the key barriers to responsible ADS certification, including failing to account for human factors like driver behaviour and situational awareness, which leads to unpredictable real-world interactions. The opacity of black-box systems complicates accountability, as the lack of transparency and predictability hinders trust and safety. Public trust in ADS is fragile, influenced by global incidents, and can lead to either over-reliance or scepticism. Emerging challenges, such as unforeseen impacts on traffic patterns and pedestrian safety, show that current certification processes are ill-equipped to handle the complexities of ADS deployment. Regulators need to build internal capabilities to anticipate these challenges effectively.

i. Risks of overlooking *human factors*

Neglecting to invest resources in understanding the human in the loop—including both drivers and VRUs—can result in systems ill-prepared for real-world conditions, where human behaviour can be unpredictable. The lack of impact assessments creates uncertainty about how ADS implementation will affect situational awareness and driver behaviour in critical scenarios, as also discovered by Banks et al. (2018). Emergent factors like deskilling, where skills such as situational awareness diminish due to increased automation reliance, create ironic challenges; drivers become liabilities in the very systems designed to enhance safety (Rowe et al., 2023). Anticipation of mixed traffic communication scenarios and aspects of intent communication with other road users involves investigating human-machine interaction factors, which is currently.

"The ADS vehicle is a very technical thing, developed by engineers, often overlooking the ecosystem where it operates." -NAR2

ii. Unclear levels of explanation expected

Unpredictability from black-box decision-making and limited controllability hinder ADS's ability to anticipate. The mandatory level of transparency on how OEMs develop and update their systems has not yet been laid down. The shift of decision-making from humans to black box systems challenges the explainability of ADS operations (Shen et al., 2022). Omeiza et al. 's (2022) survey results show that the system needs to be controllable, and this control can be exerted remotely as well, limiting user agency. **Controllability in ADS affects predictability**. Predictable and reliable system responses enhance trustworthiness and safety (Shen et al., 2022). However, the unpredictability of certain situations can lead to ethical dilemmas, making it crucial for OEMs to address these issues and for regulators to ensure discrimination prevention, a concern highlighted in 59% of the literature reviewed by Rowe et al. (2023). **The lack of predictability and controllability in ADS undermines the system's capacity for effective anticipation.** Explanations are necessary from a sociotechnical, philosophical, and legal anticipation standpoint. As safety concerns and accident reports grow, stakeholders expect ADS to make open decisions to anticipate accidents.

iii. Complex dynamics of public trust

The liminal[11] introductory phase, a state of emergence marked by fuzziness and diversity, requires the certification process to address technology-based trust (Zhang et al., 2021). To be adapted, an ADS must be trusted. ADS is a complex system, and complexity theory states that the more complex the system, the more unexpected trust is, especially in high-risk technologies (Perrow, 1999). However, trust in ADS on Dutch roads is not isolated; it is influenced by global media coverage and incidents, as seen in the public's reaction to crashes in the US, which impact the perception of ADS safety. The fickle nature of the political environment, evident in incidents like Stint (2018), leads to swift political responses towards heightened scrutiny. These **external influences are barriers to anticipating ADS certification's development goals**. Conversely, overtrust in ADS builds up quickly, leading drivers to disengage from the driving process, creating an unintended and unanticipated risk. Until meaningful efforts are made to understand the complex dynamics of public trust better, achieving effective anticipation in ADS certification might not be possible.

[11] - In the context of ADS, the term "liminal" refers to a threshold or an intermediate state where the boundaries between established practices and emerging technologies are blurred (Zhang et al., 2021).

iv. Inability to handle unforeseen emergent properties and new technology

The wicked problem of ADS lies in anticipating the consequences of deployment, as it is a complex system with extensive interrelations (Ketter et al., 2023). ADS might unexpectedly increase road congestion and urban sprawl, reducing the use of public transportation or changing commute practices to influence urban development patterns (Sperling, 2018). ADS has the potential to shift the pattern of traffic-related deaths, moving the focus from driver fatalities to the vulnerabilities of pedestrians (Koopman, 2022). While surprises are inevitable with innovation, the lack of anticipation is evident in the inability to be prepared to react effectively when new challenges or technologies arise.

v. Develop internal capabilities

Without developing internal capabilities, regulators are less equipped to anticipate and address emergent challenges in ADS certification, as they lack the expertise to proactively identify and respond to potential issues, as explained in 0.

6.2 Inclusiveness

An inclusive certification process should ensure the participation and representation of diverse stakeholders, as well as their perspectives and interests. It also means incorporating input from all kinds of end users and VRUs. Lack of inclusion directly impacts all three shared values. Insufficient training data requirements and the absence of region-specific guidelines also hinder the ability of ADS to navigate varied and unpredictable driving conditions safely.

i. Lack of mandatory inclusion

Failing to integrate societal stakeholders, such as VRUs, throughout the regulatory lifecycle undermines responsible certification efforts, as discovered in 0. Without processes to incorporate diverse viewpoints, ADS certification lacks the necessary awareness of social implications, reducing its overall acceptance and effectiveness. Neglecting the diversity of road users and infrastructure can lead to critical detection failures, as seen in past instances where ADS failed to identify motorbikes, prompting OEM adjustments only after public protests. Incomplete training datasets remain a barrier to road safety. Without proactive measures, ADS will continue to struggle with low-probability but crucial scenarios like detecting horse carriages or Halloween costumes. Lack of regulation specifying detection and response standards will leave ADS systems ill-prepared for diverse, real-world environments.

Without region-specific training data, unsafe interactions between ADS and local drivers will persist, as driving habits vary significantly across Europe. Failure to account for regional road types and markings can heighten the challenge of cross-border ADS certification. A longstanding issue carried over from human driver certification.

6.3 Responsiveness

A responsive certification process should adapt to and address feedback, concerns and changing circumstances in a timely manner. OEMs also must improve by implementing lessons learned, addressing faults and continuously refining to meet evolving safety and performance criteria. The innovation should also be responsive to social needs. Current regulations lack adaptive mechanisms, preventing real-time improvements and excluding VRUs from reporting critical safety concerns. Without swift recall processes, even minor errors in ADS can lead to significant safety risks, while delayed corrections threaten public trust and overall system reliability. The lack of anticipation in ADS development makes responsiveness an essential mitigation strategy.

i. Lack of feedback systems

The lack of feedback loops in ADS certification limits the system's internal and external responsiveness. Without these loops, assumption errors or unresolved hazards from earlier stages will persist uncorrected, as Koopman (2022) noted. Current regulations lack adaptive processes, making it difficult to respond to new data, meaning systems cannot improve based on real-time information. VRUs are often excluded from the feedback process due to the absence of a direct reporting system, which raises the reporting threshold and leads to missing valuable information. Intra-organisational communication gaps lead to repeated efforts, while differing goals and values across departments hinder unified decision-making, obstructing internal feedback loops.

Safety updates are delayed without systems to report malfunctions directly to OEMs, allowing risks to persist. OEMs are allowed to learn from system-related failures as they see fit; they are not required to do so (Who Is in Control?, 2021). A lack of a dynamic feedback system stifles the iterative development necessary for ADS to adapt to real-world conditions and meet evolving safety standards.

ii. Ability to swift recalls

"And because we are in that transition period at the moment and for the sake of public trust, it(recalls) needs to be immediate, particularly when safety concerns." -UDA

Without the necessary agility in the regulatory framework, even minor errors in boundary settings could have far-reaching consequences if not corrected promptly. If recalls are not conducted responsibly, they risk eroding trust and causing unnecessary disruptions. Without clearly defined response times in policy, delays in recalls can increase safety risks and hinder timely corrections.

6.4 Reflexivity

A responsible certification process should critically examine and question the regulator's assumptions, biases and decision-making processes. Reflexive practices involve evaluating and learning from past incidents and regulatory shortcomings while reflecting on impacts, purposes, motivations and values. A lack of a reflexive culture limits stakeholders' ability to consider broader societal shifts. Without a strong safety culture, stakeholders have little incentive to engage in this continuous reflection, meaning lessons from incidents or near misses are often overlooked.

i. *Lack of reflexive and safety culture*

Without mandatory reflexive requirements, there is no structured process for regular reflection or self-evaluation to identify biases. This leads to a short-term, ad-hoc culture that overlooks broader societal shifts and evolving road safety needs. Suppose reflexivity is not facilitated. Trust in technology extends beyond the technology itself and involves the broader social, political, and regulatory environment (McKnight et al., 2011). If reflexivity is not facilitated, stakeholders miss the holistic view of addressing public trust (Rowe et al., 2023). The lack of competencies to engage in reflexive practices further compounds this issue, with a cultural reluctance within TAAs to reflect on and learn from past decisions. Without an educational framework to improve reflexivity, this barrier remains unaddressed.

ii. *Near miss and crash database needed*

Without access to comprehensive data on incidents, near misses, and crashes, regulators are unable to fully assess the impact of their decisions or reflect on the effectiveness of existing regulations, as discovered in 4.5.2. This absence of data-driven decision-making prevents regulators from making informed adjustments to enhance safety and prevents the identification of patterns or emerging risks that could guide future improvements (Guyonvarch et al., 2023b).

This section discussed the implications of the barriers identified in each pillar of ADS certification. Anticipation is compromised by the failure to fully address human factors, transparency, public trust, and internal capabilities, leading to unpredictable risks. Inclusiveness suffers from the exclusion of diverse stakeholders like VRUs, alongside a lack of region-specific training, which leaves ADS ill-prepared for varied driving conditions. Responsiveness is weakened by the absence of effective feedback systems and delays in recalls, preventing timely safety improvements. Reflexivity is undermined by the lack of structured self-assessment and access to critical incident data, limiting the ability to learn from past decisions and foster a more robust safety culture.

6.5 Scientific relevance

The findings in this research align with ongoing discussions about the regulatory challenges in ADS certification. Coordination between regulatory bodies remains a significant issue, highlighted by Rowe et al. (2023), who stressed the importance of understanding how manufacturers and regulatory agencies shape ADS deployment. Gödker and Hornuf (2019) noted how national authorities compete to attract OEMs, leading to delays in certification processes. Similarly, Bertolini and Riccaboni (2021b) pointed out the need for reforms to address inconsistencies in rules among MS. The lack of clearly defined roles among various stakeholders in the regulatory landscape contributes significantly to responsibility gaps (Hindriks & Veluwenkamp, 2023). The findings in this research extend these studies by detailing how this regulatory fragmentation directly impacts the ability to develop a responsible certification process, reinforcing the importance of inter-organisational cooperation and improved regulatory collaboration.

Boyer and Kokosy (2022) also observed that the shift from technology-driven innovation to market pull is desired, which demands more adaptable regulations. Engstrom et al. (2020), Taeihagh & Lim (2019) and Shladover & Nowakowski (2019b) highlighted how Europe's focus on consumer protection slows innovation, contrasting with more flexible regulatory environments such as the US. This research reinforces those observations, demonstrating how regulators are ill-equipped to handle real-time ADS data. Ito and Kester (2023b) discussed how the lack of near-miss and crash data collection hinders safety management, which this research identifies as a reflexive barrier.

By addressing these barriers and building on previous studies, this research adds depth to the discussion of responsible ADS certification. It offers fresh insights into how certification processes can be improved to meet safety, legal, and sustainability goals.

6.6 Pitfalls and limitations

This section reflects on the researcher's limitations of the interview process to improve future research. The challenges that emerged majorly impacted the quality and breadth of the data collected and can be mitigated by increasing the quantity (Fernández Pinto, 2023). These limitations highlight areas where the research design could be refined to ensure more accurate and comprehensive results in similar future studies.

i. Aligning perspective

Despite providing participants with clear explanations of the study's focus before and during the interviews, some respondents initially misunderstood the focal topic. They began discussing the technology rather than the certification process, a mistake that became evident only after a significant portion of the interview had passed. This reduced the amount of usable information. The facilitator provided more examples of expected answers to correct the course, which helped clarify the focus but inadvertently introduced confirmation bias. Participants began exploiting and elaborating on the themes the examples suggested rather than exploring new ideas. The need to balance guiding the conversation without unduly influencing the outcomes remains challenging, with some traces of this bias evident in the collected data.

ii. Geographical and context generalisability

The findings of this study may have limits in generalizability mainly due to the focus on the Netherlands, where the legal and technological situation for ADS may differ significantly from that of other nations. The geographical focus limits the findings' applicability to locations with similar legal and infrastructure environments. Furthermore, the certification methodology examined in this study may not apply to other sectors or industries, as ADS has unique problems in ethics, safety, and stakeholder participation problems.

iii. Sampling limitation

The study's sample size, along with its geographical limitation, restricted the diversity of insights gathered. Participants were primarily drawn from a specific region, which may not fully represent the spectrum of barriers to ADS certification. Key stakeholder groups, particularly VRUs, OEMs, and insurance providers, were underrepresented in the study. Although some industry consultants were scheduled to represent VRUs, they withdrew at the last minute and OEMs, tier 2-3 manufacturers, and insurance representatives were also unavailable due to limited presence in the Netherlands and restricted network access.

iv. Researcher bias interpretation

The researcher's background and experiences when applying grounded theory might have influenced how data was perceived and, as a result, theme identification. Continuous verification and reflexivity were required throughout the analysis process, particularly in the later coding phases (Corbin & Strauss, 1990). Although committee members and academic colleagues regularly examined the interpretations to validate developing categories, these evaluations could have been conducted more frequently to eliminate potential bias (Johannesson & Perjons, 2014).

Attempts were made to mitigate the acknowledged limitations primarily via transparent reporting.

6.7 Future research avenues

Future research could focus on creating a risk tolerance framework that investigates how national and international risk tolerances influence ADS safety requirements. This would entail examining societal risk acceptability and determining the degree of danger the public is prepared to tolerate from ADS vs human drivers. A cost-benefit analysis of incremental safety enhancements can determine the economic viability of pushing ADS safety beyond present standards. Establishing a technical definition for competent driving is necessary for standardisation but requires experimental research. Finally, research into dynamic safety standards would aid in understanding how safety expectations change over time, particularly as ADS technology progresses, and ensuring certification processes stay relevant and effective. The high degree of interlinkage among the identified barriers suggests the need for further analysis through causal research.

7. Recommendations

Identifying definitive solutions to overcome each barrier lies beyond this research's scope. The following chapter presents a compilation of solution frameworks proposed by various participants, reflecting a call for action from diverse perspectives. Given the presence of diverse and conflicting technological approaches and the early phase of ADS development and adoption, proposing concrete solutions at this juncture may be premature. Instead, prioritising targeted research on the identified barriers emerges as a prudent next step to inform and guide effective future strategies. The following recommendations could help Dutch regulators not only improve their ability to certify ADS responsibly but also serve as a long-term investment in building capabilities to address other rapidly evolving technologies.

7.1 Build organisational resilience

Regulators are encouraged to establish processes to tackle complex problems systematically. Regular assessment of internal capabilities helps anticipate and stay aligned with the evolving technological innovation requirements through robust audits and independent research. By leveraging organisational capabilities- information ecosystem and employee expertise, regulatory bodies could utilise their intangible assets and ensure they stay ahead of the curve, safeguarding public interests in a rapidly changing landscape (Lawson & Samson, 2001).

Developing a reflexive culture emphasising regular introspection and balancing generalists with specialists may allow regulators to adjust throughout the ADS lifecycle and maintain preparedness. Embedding a strong safety culture within the certification process, with inspectors trained to adapt to technological advancements, could enhance effectiveness.

7.1.1 **R1:** Invest in internal skill and culture development

Expanding organisational capabilities by enhancing the specialised expertise of employees is an effective way for regulators to proactively anticipate and address emerging challenges. If regulators gain expertise in areas like cybersecurity, they can mitigate risks that may not be immediately apparent, ensuring a more robust certification process.

“These are complete new knowledge areas where we also still need to develop the knowledge" - NMR

The ability to identify unknown unknowns hinges on having regulators who thoroughly understand the technology (Hoonsopon & Ruenrom, 2012) and also enhances the regulator's ability to conduct thorough audits and independent research as per GAR. The ecological footprint, infrastructure expense, and psychological effects, such as induced user anxiety, are still not well-researched but should be included in the criteria of the decision-making process (Wei, 2023). Regulators must develop confidence in critically assessing the claims made by ADS developers, which requires them to understand the underlying technology.

A proactive approach to risk management enhances the safety of ADS and builds public trust in the regulatory process. However, relying on external consultants to inform about potential risks is not sustainable as it creates a constant knowledge gap and delays anticipation. Test inspectors must be trained to have prior exposure to complex systems to build the decision-making abilities ADS demands via open norms.

Reflexive culture mandates constant introspection, requiring Organisations to regularly assess and adjust their internal capabilities to meet the changing needs of the technology (Stilgoe et al., 2013). Regulators must continuously restructure, maintaining an optimal balance between generalists and specialists who can provide both broad oversight and in-depth technical expertise as per GMR. Management must remain reactive, adjusting their approach according to ADS's lifecycle stage and guaranteeing preparedness by investing in a reflexive culture.

A safety culture prioritises safety in every aspect of the regulatory process, from initial design assessments to final certification. Inspectors must be proactively trained to adapt to changing technology and regulatory frameworks to ensure effectiveness. Cultivating a culture of innovation and safety guarantees that they can enforce current standards while detecting and responding to developing difficulties in ADS certification.

7.1.2 **R2:** Leverage learning platforms

Regulators must actively facilitate knowledge exchanges and incubating platforms that can help the Dutch ADS community develop and help regulators grow. They are in a powerful position to align investment in innovations with the triple helix approach to include diverse perspectives of industry stakeholders and academic institutions (Werker et al., 2017). By regularly hosting forums, workshops, and collaborative platforms, regulators can create dynamic environments that help them stay updated with industrial innovations. Through these systems, regulators can gather insights into current certification practices' effectiveness and make necessary real-time adjustments.

7.1.3 **R3:** Research-driven shift from conservative regulation

Being responsive in regulation requires equipping regulators with the tools and knowledge to make informed decisions swiftly. The absence of concrete arguments often leads to delays in reaching consensus. By developing internal capabilities, regulators can strengthen their ability to present well-founded arguments for introducing innovation with well-calculated risk benefits backed by thorough research and data. NAL's recommendation on using econometric and causal modelling approaches to navigate complex systems and mitigate emergent properties is an approach to increase confidence in decision-making.

7.2 Stimulate innovation

The absence of government-initiated measures to stimulate innovation and the lack of attempts to foster a learning community are barriers to new product developers' entry and hinder investments in innovations (Porter, 2008). An agile regulatory approach, focused on incremental improvements, can effectively manage risk by starting with lower-risk scenarios, such as limiting vehicle speed, which can provide valuable input into the regulatory process. Implementing pilot programs and sandboxes would enhance responsiveness by allowing early identification of issues.

7.2.1 **R4:** Build regulatory sandboxes

Regulatory sandboxes can fill this gap but are missing in the Dutch ADS ecosystem, points GAR. Tartaro et al. (2023) emphasise the importance of balancing regulation with innovation to achieve both safety and technological advancement. This calls for creating a regulatory environment suitable for innovation with pilot programmes allowing for an agile development approach that relies on incremental regulation improvements. The absence of feedback loops within the regulatory framework hinders effective learning. NCD highlighted the importance of starting with lower-risk scenarios—such as allowing driving at 30 km/h instead of 50 km/h—and gradually increasing speed as confidence in the system grows. This approach reduces the risk of large-scale failures by identifying potential issues early in development, enabling quick adjustments (McKinsey, 2021).

7.3 Mandate inclusion

"The essence of technology is by no means anything technological." –Heidegger (1977).

The complexity of ADS requires technical knowledge and a comprehensive understanding of societal impacts, which can be achieved through inclusive practices. In an uncertain environment, including every perspective affected by ADS is necessary to ensure responsible steps towards ADS alignment. Without mandating inclusion at every stage of the regulatory development process, societal risks are overlooked due to the high effort required, and the potential benefits remain uncertain. The next set of recommendations advises including three key stakeholder categories: the Dutch regulatory ecosystem, international authorities, and end-users. These recommendations focus on improving coordination, enhancing collaboration, and involving stakeholders early in the certification process.

7.3.1 **R5:** Streamline Dutch regulatory communication

ADS, being a complex technology, involves various stakeholders such as RDW, CBR[12], IenW[13], and others, with many additional stakeholders likely still undiscovered and thus involved. Each organization has its way of working, with different incentives and processes. This complexity requires further research into organizing effective collaboration methods, delineating responsibilities to prevent duplication and redundancies, and utilising the full potential of the Dutch regulatory landscape for responsible ADS certification. Additionally, it is essential to establish techniques that improve shared understanding to reduce potential miscommunication and mandate constant inclusion throughout the regulatory lifecycle without significantly delaying the introduction of ADS. ADS has the potential to shift focus from isolated vehicle safety to a system of traffic safety, which calls for effective multi-stakeholder engagement.

7.3.2 **R6:** Investigate societal stakeholders engagement strategies

Public participation in transportation policy has the potential to transform the sector but often falls short, leading to reduced confidence in inclusion from regulators. Executing processes to increase participation are resource intensive, adding reluctance, as per Sørensen et al. (2023). This research advocates for innovative, deliberative approaches to tackle challenges like representativeness and participation burdens, emphasizing the need for more experimental research to establish effective inclusion strategies. Involving stakeholders in early phases - coordinating approval processes with local governments for localized deployment case studies and creating open platforms that invite trials and citizen interaction can enable co-development. Technology familiarity enables public trust (Horowitz et al., 2023). Proactive acquaintance with potential impacts and awareness of ADS limitations further support informed public engagement.

7.3.3 **R7:** Understand human factors

As discussed in 6.1, understanding human-ADS interaction and integrating user experience into the certification process is essential to ensure that systems support rather than hinder drivers. Addressing cognitive load and driver disengagement through human-centric testing will help design safe and effective ADS in real-world conditions until humans are expected to be in the decision-making loop. Resources in understanding theoretical frameworks like MHC, which emerged in **Error! Reference source not found.**, could ensure human oversight, followed by strategies to

[12] The Dutch human driver licensing authority, is responsible for conducting driving tests and issuing driving licenses while ensuring that drivers meet the necessary health and competency standards.
[13] Ministry of Infrastructure and Water Management oversees policies related to infrastructure, water management, and transport.

ensure integration into the decision-making processes. This will enhance the ADS's ability to align with human values, balancing safety with operational goals.

7.3.4 **R8:** Ensure diversity is addressed

As discussed in 4.6.1, certifying the vast number of possibilities ADS encounters without raising certification time and costs complicates ensuring that ADS sufficiently addresses diversity. Further research into probabilistic validation techniques, which require regulators to place greater trust in OEMs, can help tackle the complexity and suggest a paradigm shift in execution methods. Establishing global data-sharing partnerships and developing infrastructure to collect data from underrepresented areas can ensure that ADS systems are trained in diverse, real-world driving environments.

7.4 Improve feedback loops

ADS is expected to evolve constantly; thus, reliance on continuous regulatory improvement becomes essential, even if it challenges legal rigour. Regulatory systems must not compromise safety while still encouraging innovation. Feedback systems allow for easy and direct access to information on efficacy, ensuring that ADS remains responsive and aligned. Investment is required in researching ways to develop feedback loops that foster easy and direct access to information across the stakeholder value chain—between end-users, regulators, and OEMs—which is increasingly essential for adapting ADS, previously underdeveloped in a stationary certification process.

7.4.1 **R9:** Create a centralised public platform

A government-run platform would provide a single access point for all stakeholders—developers, regulators, and the public—to obtain up-to-date information on regulatory developments. This platform would address the issue of unapproachable authorities and reduce uncertainty about regulatory timelines, ensuring developers have the sustainable clarity needed to plan projects and secure funding. A detailed explanation of regulatory decisions would foster a better understanding of the regulatory landscape among all stakeholders.

The platform can potentially build a public database of incidents, such as crashes and near misses, along with subsequent investigation reports. Sharing this information openly would help improve safety standards across the industry by exchanging relevant information and enabling adaptation. As the ADS system evolves, the platform would serve as a valuable resource for tracking progress, identifying emerging risks, and ensuring that certification requirements are updated to reflect the latest standards.

7.4.2 **R10:** Implement agile governance

Invest in exploring and optimising certification strategies to handle the influx of new ADS capabilities without causing significant implementation delays. Traditional regulatory frameworks often struggle with the dynamic nature of technology, deeming it inapplicable to deviations. Combined with the certification capabilities expected due to OTA being much higher than currently, research into certification strategies to optimise the certification timeline is required. Certification would require a combination of simulations, self-certification, and real-world testing, balancing the trade-offs between resources (people, time and money) exploited and safety, legal rigour, and long-term sustainability expected. An agile approach, starting with a low-risk threshold ODC—limiting speed and controlling the exploration of unknowns —alongside stable feedback loops will balance safety while nurturing ADS development. Agile governance can bridge the lifecycle gap between technology and regulations by providing a mechanism to periodically innovation policy to maintain relevance.

8. Conclusions

This thesis aimed to investigate the barriers to certifying Automated Driving Systems (ADS) from the lens of Responsible Innovation (RI). Despite ADS holding transformative potential (ecological impact, traffic and city planning, health and safety, and micro- and macroeconomic benefits), the certification process lacks a responsible development approach. This research sought to address this gap by identifying the **barriers to responsible ADS certification on Dutch roads**, using qualitative research to uncover social and technological obstacles.

Twenty-one industry-wide experts identified twenty-seven barriers, and five validated and prioritised the findings. A prominent theme that emerged was the need for regulators to be prepared for the complexities involved in emerging technologies and the lack of preparedness to tackle innovation. Regulators are limited by lack of inter-organisational coordination and insufficient internal capabilities. These challenges are compounded by the absence of a reflexive culture, which is needed to gain a forward-looking approach to mitigate the asynchronisation between regulatory and technological lifecycles.

The lack of societal engagement remains challenging, mainly excluding vulnerable road users from decision-making processes. A core unresolved question is what constitutes "safe enough" for ADS, which depends on societal consensus and is complicated by the tension between strict regulation and the need for innovation. Governance structures need to be optimised to certify operational design conditions and in-use data monitoring, but regulators currently lack the technological and operational capacity to tackle these tasks. While normative shifts occur with open norms, insufficient real-world testing remains a barrier to responsible certification. This research offers a foundation for further research to resolve these barriers systematically.

Value analysis revealed three values guiding ADS certification: safety, sustainability, and legal rigour, with trade-offs involving resources required for responsible innovation, such as time and money. Decision-makers are called upon to balance these competing interests and set priorities that reflect a consensus among diverse stakeholders. Embedding RI’s pillars—anticipation, inclusion, responsiveness, and reflexivity— into the certification process, regulators can ensure that their strategies are aligned with societal values. This study found that anticipation is compromised by insufficient attention to human factors and the black-box nature of ADS. The absence of mandatory inclusion undermines inclusiveness, responsiveness is weakened by the lack of a robust feedback system, and reflexivity is not yet embedded within the organisational culture of regulators and stakeholders.

This is the first of its kind research that offers ten recommendations to help regulators strengthen their ability to manage ADS and future technologies, focusing on three main areas. Strengthening organisational resilience involves investing in internal skill development and building a culture that supports continuous learning and adaptation. Effective stakeholder engagement requires creating more inclusive processes that involve a broad range of voices in the certification process, particularly those from vulnerable road users and societal stakeholders. Agile governance strategies are necessary to ensure regulatory frameworks can quickly adapt to technological advancements, including improving feedback loops and implementing flexible, responsive policies.

Despite these findings, it is essential to acknowledge the limitations of this research. The study focused on the Dutch regulatory context, which may limit the generalisability of the results to other countries or industries. Moreover, as a qualitative study, the research methodology has inherent limitations related to sampling and potential biases introduced by the researchers' contextual understanding. Nevertheless, this research's primary contribution lies in identifying twenty-seven barriers prioritised according to their severity and complexity. This prioritisation provides a strategic framework for regulators, helping them allocate limited resources effectively and responsibly. While all identified barriers must be addressed to achieve responsible ADS certification, the findings offer decision-makers a clearer understanding of the efforts required and the impact of addressing each barrier. The findings accelerate the certification process and ensure that RI is embedded in ADS certification.

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Appendix A

Overview of certification processes

The current multi-stage certification process laydowns procedure for the complete spectrum of stages, from prototype evaluation to necessary recalls to prevent non-compliant vehicles from circulating. The process is overseen by several entities that coordinate to maintain stringent standards at National and EU levels. Technical Services (TS) conduct tests, including Real Driving Emissions (RDE) tests, after which Type Approval Authorities (TAA) grant approvals, and Market Surveillance Authorities (MSA) ensure compliance of vehicles already on the market (Regulation (EU) 2018/858, 2023). In the Netherlands, RDW performs the three critical functions of a TAA MSA and conducts RDE testing. With the introduction of ADS, the role of TAA and TS now also includes collecting additional information on the development processes and adapting to a combination of testing methods, including simulations, test track and real-world testing (European Commission. Joint Research Centre., 2024). RDW collaboration with around 30 designated Dutch TS that are authorized to conduct tests and certify products but also accept test reports from TS designated by other member states, and with the changing nature of certification, the nature of this collaboration will change (Blanco et al., 2020).

To identify potential issues early in the development process, the first stage evaluates prototypes from manufacturers in collaboration with TS for aspects such as emissions, safety features, and overall performance. The next stage involves detailed inspections, including RDE tests, to address the discrepancies between lab results and actual on-road performance, ensuring compliance with regulations. Preventing environmental misconduct is crucial in maintaining public trust, especially after the Volkswagen emissions scandal of 2015, triggering a contagion effect highlighting that violations in one firm can harm the financial performance of related firms in the industry (Bouzzine & Lueg, 2020).

Only after completion of all specified tests is the vehicle granted type approval by the national TAAs, and each vehicle produced under this approval is accompanied by a Certificate of Conformity (CoC), which certifies that the individual vehicle matches the approved type. Alongside a Conformity of Production (CoP) is an ongoing verification process that ensures the manufacturer's production process consistently produces vehicles that conform to the type approval standards, which will also increase the operational workload with constantly updating software-reliant vehicles (Blanco et al., 2020).

To maintain compliance, MSAs are essential in keeping an eye on vehicle performances after they are sold. They resolve any violations of established norms by randomly inspecting and testing cars that are currently in operation. This monitoring includes handling recalls, in which law enforcement works with manufacturers to address safety or compliance concerns that are discovered. Significant reforms were introduced after the 2015 scandal, including the enhancement of the

European Commission's powers to oversee national authorities, the introduction of the Worldwide Harmonised Light Vehicle Test Procedure (WLTP) and the introduction of third-party testing (European Court of Auditors, 2019).

Major regulations addressing ADS

United Nations Regulations 155, 156, 157.

UN Regulation No. 155 mandates cybersecurity standards for vehicle approval, focussing on managing and mitigating cyber threats. UN Regulation No. 156 outlines requirements for software updates, ensuring vehicles maintain integrity and safety through controlled updates. UN Regulation No. 157 sets standards for Automated Lane Keeping Systems, including safety measures, fail-safe responses, and data storage requirements (Sever & Contissa, 2024).

European Union Framework

EU Regulation 2019/2144, effective from September 2022, aims to create a unified safety standard across borders. It includes performance requirements for ADS approval and compliance assessment procedures for testing and evaluation. Additionally, Commission Delegated Regulation (EU) 2022/2236 amends requirements for vehicles with fully automated systems, while Commission Implementing Regulation (EU) 2022 provides detailed technical requirements for automated vehicles (Sever & Contissa, 2024).

EU Regulation 2022/1426, effective August 2022, sets forth specific procedures and technical requirements for the type-approval of ADS. It aims to ensure technical compliance and interoperability across the EU, building on the foundational safety guidelines established in Regulation 2019/2144. Regulation 2022/1426 aims to establish the criteria and standards necessary for fully automated vehicles to be approved and enter the market across EU member states, highlighting the EU's move towards accommodating advanced automated vehicle technologies on its roads (European Commission, 2022).

Experimenteerwet Zelfrijdende Auto

The Law Governing the Experimental Use of Self-Driving Vehicles, an amendment to the Road Traffic Act, was a progressive approach to regulating ADS, focussing on flexibility and experimentation rather than creating entirely new laws (*Netherlands*, 2017). This step highlights the importance of regulation in facilitating the development of ADS.

Appendix B

Initial recruitment mail

Subject- Request for a 45-minute interview

Greetings *xx*[14],

I am contacting you for your expertise in *smart mobility*[15] would be an ideal fit for my Mater's Thesis research. To quickly introduce myself, I am a research intern at the RDW and in collaboration with TU Delft's research ecosystem and am exploring Autonomous Vehicles certification. I am addressing the problem from the lens of responsible innovation and involves qualitative research from various stakeholders' perspectives. Your inputs will represent ADS *regulator*'s [16] viewpoint and feed the framework to lay down the recommendations for responsibly certifying Autonomous vehicles to improve Road safety and security. I can present more information regarding the expected outcomes during the interview or over a quick virtual coffee conversation earlier as well.

This mail is to schedule a 45-minute interview with you anytime in *June* to gather your expert insights. If you can send me a couple of available slots, I can schedule it right away. The data collected will be anonymised and publicly available on the TU Delft repository and the journal/conference chosen at a later date. Looking forward to meeting you and learning from you. Have a nice week ahead.

Met vriendelijke groet, Warm regards,

Vaibhav Anand

MSc Management of Technology

Technology, Policy and Management | TU Delft

Thesis Intern – VRT-TI Experts

[14] Placeholder
[15] Based on individual's expertise
[16] Stakeholder group

Follow up email

Greetings xx,

Firstly, I want to thank you for taking the time to participate in my research. The interview will take place in room xx/online @link from xx.

In this mail, I will introduce my topic and your role in this research. I have also attached a consent form, which you must sign before we can start the interview. All responses will be stored on TU Delft servers and can only be accessed by the committee professors. Only Anonymised responses will be present in the public version of the report. Please don't hesitate to ask any questions related to the research, and I will reply promptly.

Research Question- What are the barriers to responsibly certify Autonomous Vehicles on Dutch roads?

This research is not intended to be a technical deep dive into specific barriers but a socio-technical study aimed at understanding the higher-level system factors that influence the responsible certification of ADS. It is highly recommended that participants refrain from delving into detailed discussions on the dynamics of particular factors for an extended period. Instead, the focus should be on identifying and discussing all possible barriers in order of their importance.

Can you help me understand your expertise?

CDEI, UK, has identified six themes for Responsible Certification: Road Safety, Data, Fairness, Explainability, Public Trust, and Governance. Due to the limited time available, I want to request that you share the three themes you are most comfortable elaborating on in order of convenience. I will ask follow-up questions to ensure that we can cover at least the barriers associated with these themes.

This qualitative research explores the ethics of ADS from a responsible innovation perspective. The stakeholder inputs are compiled to form a framework of all current barriers to responsible innovation. We are interested in understanding your perspectives on the factors that should be considered in responsibly certifying ADS and the challenges encountered in achieving these values. Your insights will be synthesized with inputs from other stakeholders to identify common barriers and areas of conflict that need to be addressed. This framework will guide the formation of the certification process and ensure alignment with stakeholder values and objectives. The framework is structured as follows-

Figure 10: The barrier-lifecycle matrix for ADS certification *attached*

The interview will be conducted using a semi-structured format, allowing for flexibility to explore diverse perspectives and insights. It will involve open-ended questions and probing to delve deeper into themes chosen by you. The interview will initially understand your interpretation of responsible innovation and what that means for the certification process of ADS.

"According to RDW's values, what criteria must be met for the certification process to be considered responsible? How does RDW define responsible certification in the context of autonomous vehicle certification?"

In line with the principles of Responsible Innovation, the next part of the interview will focus on four key dimensions: Anticipation, Reflexivity, Inclusiveness, and Responsiveness. These dimensions serve as guiding principles for understanding and addressing the challenges associated with responsible certification of AVs. During the analysis stage, the insights gathered from stakeholders will be grouped into seven thematic areas identified CDEI and further divided into five stages of certification process.

Each dimension of Responsible Innovation plays a crucial role in achieving these objectives and your understanding of each dimension would be helpful.

1. Anticipation: Anticipation involves identifying and assessing potential impacts, risks, and opportunities associated with emerging technologies. In the context of AV certification, anticipation helps anticipate safety risks, regulatory challenges, and societal implications, enabling proactive measures to address them.

2. Reflexivity: Reflexivity entails critically examining and questioning assumptions, biases, and decision-making processes throughout the innovation lifecycle. In the context of AV certification, reflexivity prompts stakeholders to reflect on past incidents, systemic issues, and regulatory shortcomings, fostering continuous learning and improvement.

3. Inclusiveness: Inclusiveness emphasizes the participation and representation of diverse stakeholders, perspectives, and interests in the innovation process. In the context of AV certification, inclusiveness ensures that the certification process considers the input of communities, advocacy groups, and marginalized populations, leading to more equitable outcomes.

4. Responsiveness: Responsiveness involves adapting and addressing feedback, concerns, and changing circumstances in a timely manner. In the context of AV certification, responsiveness enables stakeholders to address safety incidents, emerging risks, and stakeholder feedback effectively, enhancing the credibility and trustworthiness of the certification process.

The overall Questionnaire will look like this for your reference-

Table 11: Semi structured interview guide attached

If you want to investigate further, the academic version of the questionnaire explanation and interview protocols can be found here[17].

[17] Link retracted due to high similarity with Chapter 3: Research methodology.

Thank you again for your participation. I look forward to your signed consent form and top 3 preferred themes. Have a nice week ahead.

Met vriendelijke groet, Warm regards,

Vaibhav Anand

MSc Management of Technology

Technology, Policy and Management | TU Delft

Thesis Intern – VRT-TI Experts

Participant consent form template

Delft University of Technology
HUMAN RESEARCH ETHICS
INFORMED CONSENT FORM- Vaibhav Anand
(English Version: January 2022)

You are being invited to participate in a research study titled "Developing a Framework to Responsibly Certify Autonomous Vehicles on Dutch Roads" This study is being conducted by Vaibhav Anand candidate, an MSC. Thesis researcher from TU Delft, in collaboration with RDW, the thesis internship provider.

The purpose of this research study is to investigate stakeholder perception of autonomous vehicles certification and its potential impact on their adoption. Your participation will involve answering interview questions about your attitudes and opinions regarding autonomous vehicles. It is estimated to take approximately 45-60 minutes to complete. The data collected will be used for academic research purposes, including publication and informing policy decisions. During the study, you will be asked to answer questions about your perceptions of autonomous vehicles and their potential benefits and risks.

Given that this study involves online activity, it is important to acknowledge the potential risk of a breach. We assure you that all your responses will be treated confidentially to the best of our ability. Measures will be taken to minimize risks, including ensuring anonymity and secure storage of data.

Participation in this study is voluntary, and you may withdraw at any time without penalty. You are also free to skip any questions you prefer not to answer. Please note that data collected from you will be retained for a period of 5 years following the completion of the study, after which it will be securely deleted.

For any questions or concerns about the study, please contact Vaibhav Anand at v.m.anand@student.tudelft.nl or Dr. Jan Anne Annema at J.A.Annema@tudelft.nl

Figure 19: Consent form - Part 1

Explicit Consent points

PLEASE TICK THE APPROPRIATE BOXES	Yes	No
A: GENERAL AGREEMENT – RESEARCH GOALS, PARTICPANT TASKS AND VOLUNTARY PARTICIPATION		
1. I have read and understood the study information dated [*DD/MM/YYYY*], or it has been read to me. I have been able to ask questions about the study and my questions have been answered to my satisfaction.		
2. I consent voluntarily to be a participant in this study and understand that I can refuse to answer questions and I can withdraw from the study at any time, without having to give a reason.		
3. I understand that taking part in the study involves: • Participating in an interview. • The information from the interview being captured through audio recording. • The audio recording being transcribed into text for analysis purposes. • Your consent to the audio recording being obtained prior to the interview. • Ensuring the confidentiality of your responses by securely storing and anonymizing the transcripts. • The audio recordings being destroyed after transcription to maintain anonymity and data security.	☐	
B: POTENTIAL RISKS OF PARTICIPATING (INCLUDING DATA PROTECTION)		
4. I understand that participating in the study also involves collecting specific personally identifiable information (PII) such as designation, organisation and associated personally identifiable research data (PIRD) with the potential risk of revealing my identity.		
5. I understand that the following steps will be taken to minimise the threat of a data breach and protect my identity in the event of such a breach, including anonymous data collection, pseudonymization, secure storage, limited access and transcription.	☐	
6. I understand that the (identifiable) personal data I provide will be destroyed after publishing relevant research papers and theses.		
C: RESEARCH PUBLICATION, DISSEMINATION AND APPLICATION		
7. I understand that after the research study, the de-identified information provided will be used for reports, publications, and potentially framework development related to autonomous vehicles, with possible inclusion of recognizable quotes.	☐	
8. I agree that my responses, views or other input can be quoted anonymously in research outputs	☐	☐
D: (LONGTERM) DATA STORAGE, ACCESS AND REUSE		
9. I give permission for the de-identified responses that I provide to be archived in TU Delft repository so it can be used for future research and learning.	☐	

Figure 20: Consent form - Part 2

Signatures

__________________________ __________________________ ________

Name of participant [printed] Signature Date

I, as researcher, have accurately read out the information sheet to the potential participant and, to the best of my ability, ensured that the participant understands to what they are freely consenting.

________________________ __________________ ________

Vaibhav Anand Signature Date

Study contact details for further information: Vaibhav Anand, +31-0626534959, v.m.anand@student.tudelft.nl

Figure 21: Consent form - Part 3

Recruitment events

Table 10: Recruitment events

Event	Location	Date
ADAS lab opening	Lijm & Cultuur, Delft	23/05/24
Self-driving challenge	RDW Testcentrum, Lelystad	14/06/24
Formula Student Netherlands	TT Circuit, Assen	13/07/24 – 18/07/24

Appendix C

Interview protocol

Table 11: Semi structured interview guide

Interview phase	Time interval	Introduction text	Interview question
Briefing Phase	0-1	Introduce Topic, RQ, Their role. I am Vaibhav, a TU Delft Master's in Management of Technology student and this is my qualitative thesis research. I am questioning the barriers to responsible certification of Autonomous Vehicles on Dutch roads. This is a socio-technical and ethics study aimed at understanding the higher-level system factors that influence the responsible certification of ADS and not a technical deep dive. Focus should be on identifying and discussing all possible barriers. I explore stakeholder perspectives and combine them into a framework that will guide the formation of the certification process. I have allocated time for each question, I would give you an indication by clicking on my phone but feel free to continue as we have buffer and questions are structured in order of their priority.	
Warm-up Phase	2-4		Can you please introduce yourself and your department's role in ADS certification?
Warm-up Phase	5-9	So you are an *RDW* representative today.	According to your values, what should responsible certification of ADS include? Ideal world scenario - Barriers of transitioning from closed to open norms.
Introduction to the Analytical Framework	10-11	Present the Framework. To bring some order into our understanding. • 5 stages of certification by CDEI, UK • 4 dimensions of Responsible Innovation. In order to say that the certification process has been responsibly innovated, we need to ensure that we have anticipated, reflected, been inclusiveness and been responsive. • 6 themes that responsible innovation cluster into as per the UK's framework. Explain, I will not mention the 2 aspects later but extract from your answers what is relevant for which cell. • Data is Privacy and Sharing	
Anticipation	12-18	We have to be anticipative in the certification process which means proactive and forward-looking approach taken to identify potential impacts, risks, and opportunities associated with emerging technologies or innovations and feed it back to the design. For us it means addressing road safety implications and other negative externalities of introducing ADS.	What are the barriers to ensuring that the ADS certification process is anticipative? • 15-16 ~ What is preventing us from ensuring Anticipation for road safety?

			• Next 2 values based on expert preference. In improving Explainability what are we not able to anticipate rn.
Inclusivity	19-25	We have to be inclusive in the certification process. Inclusiveness generally means ensuring the participation and representation of diverse stakeholders, perspectives, and interests. It also means incorporating input from all kinds of end users and VRUs—pedestrians, cyclists, and the ecosystem around ADS.	What are the biggest barriers in ensuring that the ADS certification process is inclusive? • 24- 25 What is preventing us from ensuring Inclusivity for road safety? • Next 2 values based on expert preference. Training data
Responsiveness	26-32	We have to be responsive in the certification process. Responsiveness generally means adapting and addressing feedback, concerns, and changing circumstances in a timely manner. And the innovation needs to be responsive to social needs. Is the certification process so organized that it can respond to new insights and developments (including surprises)?	What are the primary obstacles hindering the agility of the ADS certification process? Focus on recalls. • 29- 30 What is preventing us from ensuring responsiveness for road safety? • Next 2 values based on expert preference. Updates
Reflexivity	33-39	We have to be reflexive in the certification process. Reflexivity generally means critically examining and questioning our assumptions, biases, and decision-making processes. Reflexivity in certification process generally means evaluating and learning from past incidents and regulatory shortcomings. Do the involved actors reflect on impacts, purposes, motivations and values?	What are the biggest barriers in ensuring that the ADS certification process is reflexive? • 36- 37 What is preventing us from ensuring reflexiveness for road safety? • Next 2 values based on expert preference.
Buffer	40-45	Bring back to my first question.	- What is stopping us from saying that this ADS is responsibly certified. You can recall your answers What is RDW need to change? In improving Explainability what are we not able to anticipate rn. Which direction do we need to look into to improve From a governance perspective when can we say that the certifi process is inclusive.
Participant Feedback	45+	Thank you for your participation, I will share the transcript for review and the final thesis once done. Any questions for the process.	- Is there anything more you would like to add that did

	not fit the questionnaire but would be relevant for this research? - Any feedback or clarification to the methodology? - Can you recommend more participants?

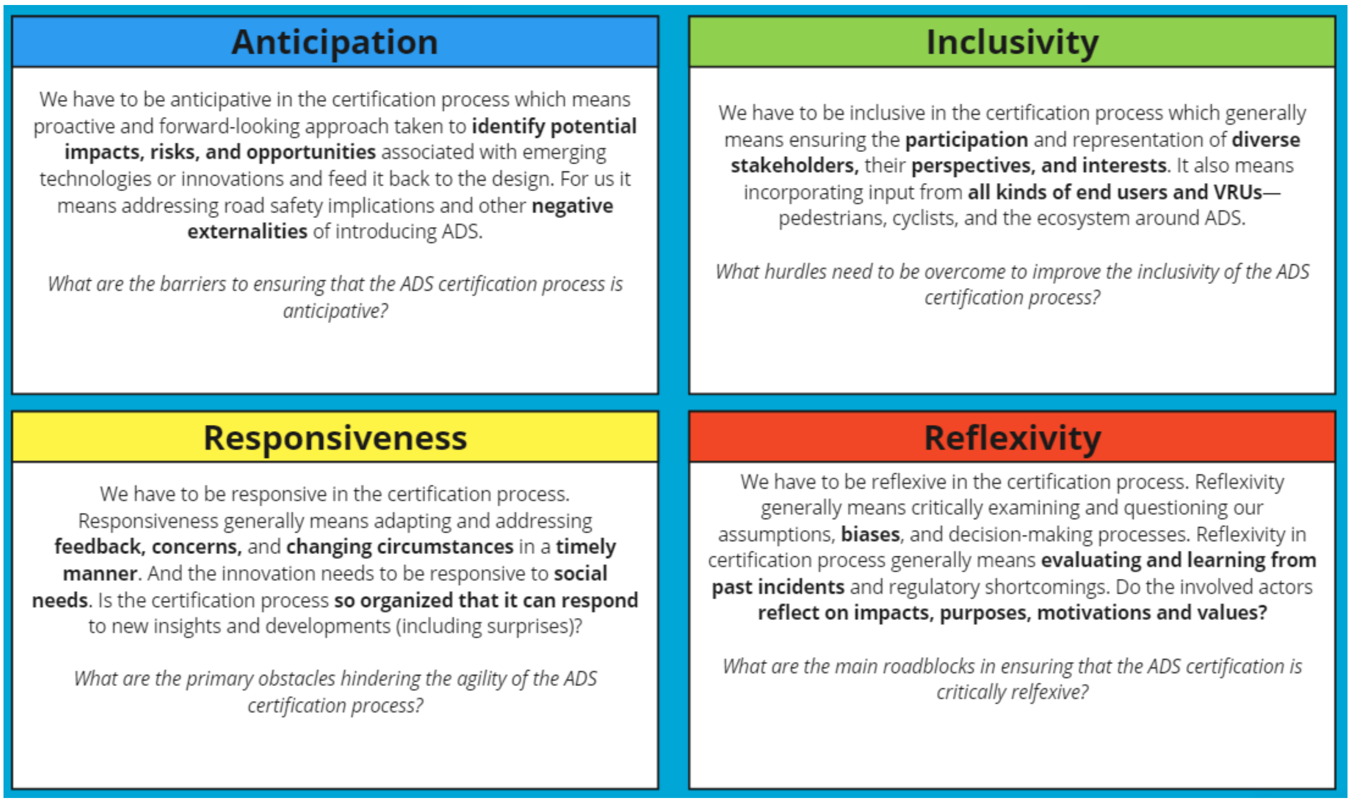

Figure 22: Visual aids used during the interviews

Appendix D

Material provided in the feedback session

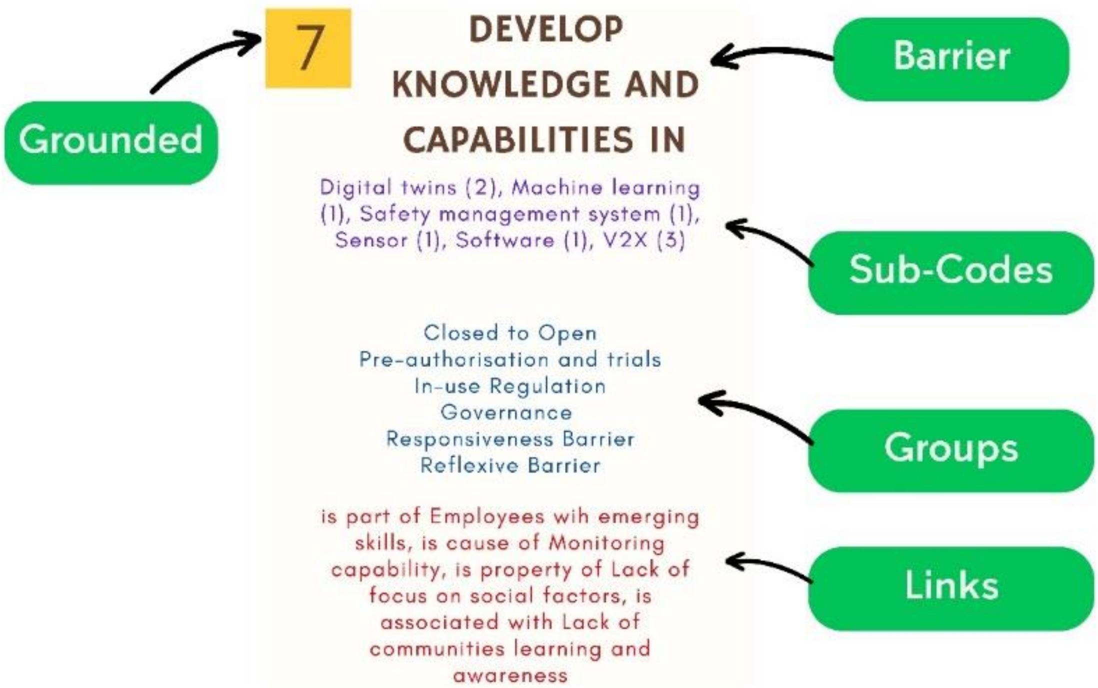

Figure 23: Reading guide for cards used

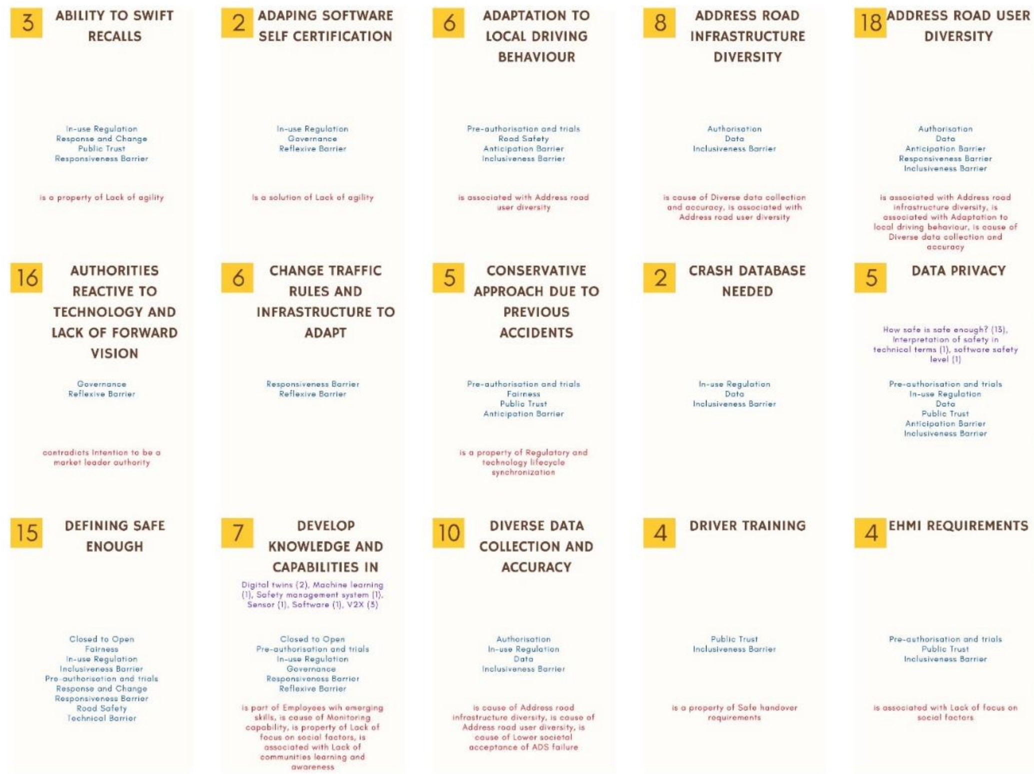

Figure 24: Open, axial and selective code cards - Part 1

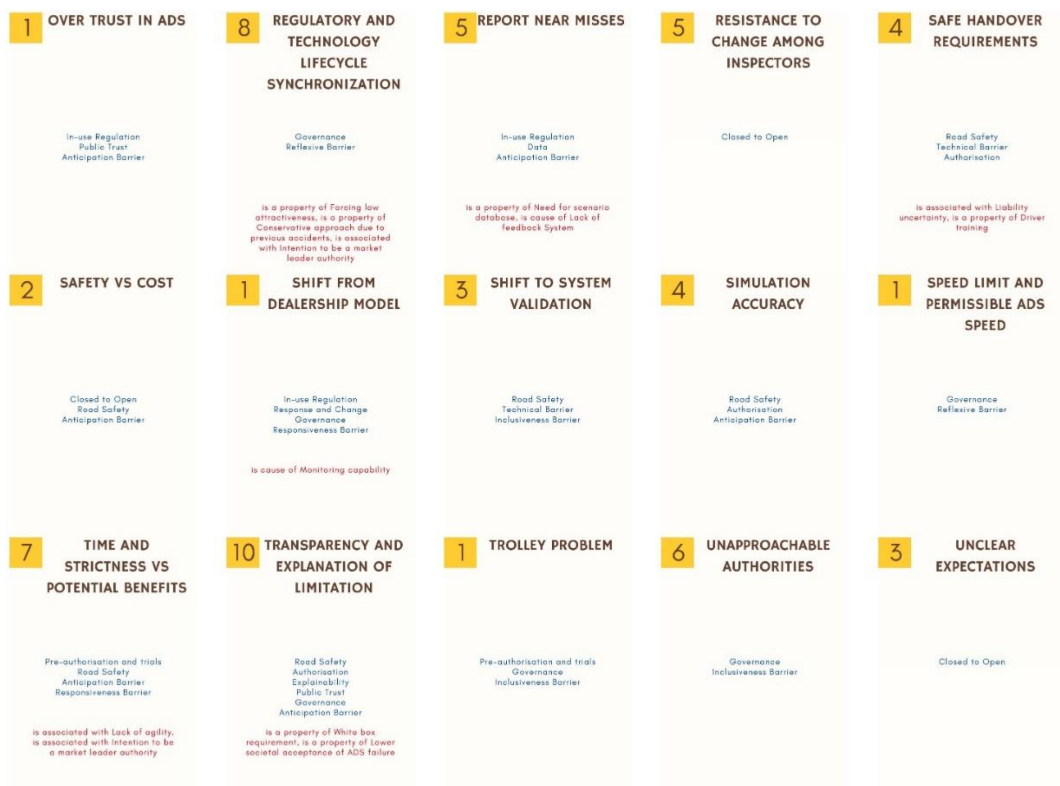

Figure 25: Open, axial and selective code cards - Part 2

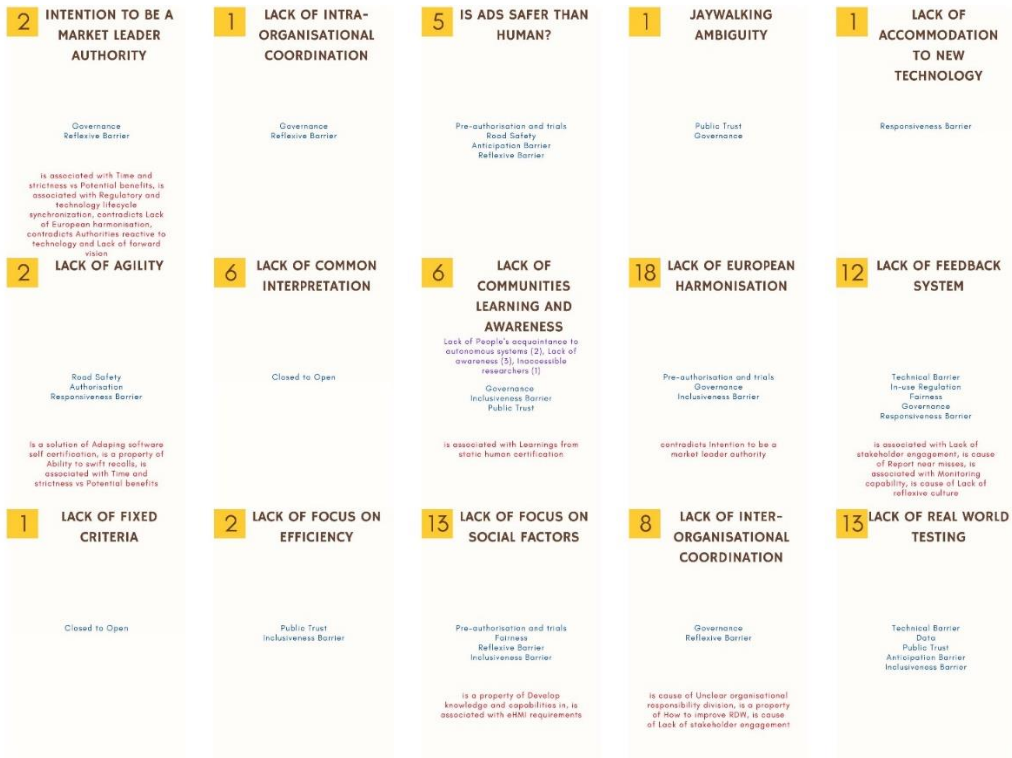

Figure 26: Open, axial and selective code cards - Part 3

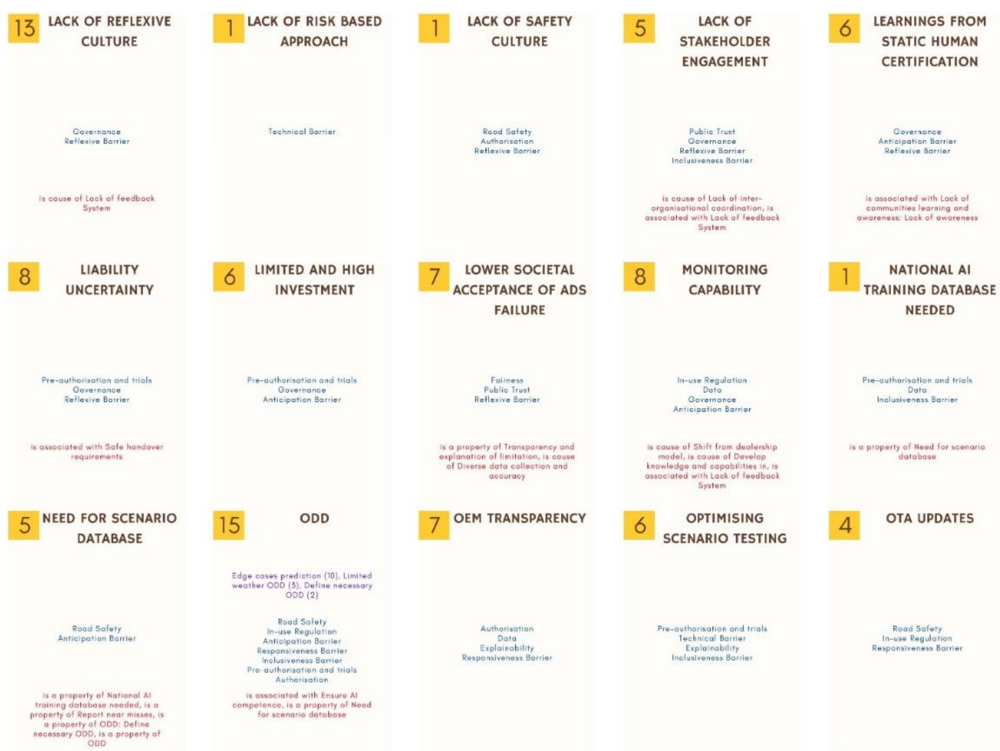

Figure 27: Open, axial and selective code cards - Part 4

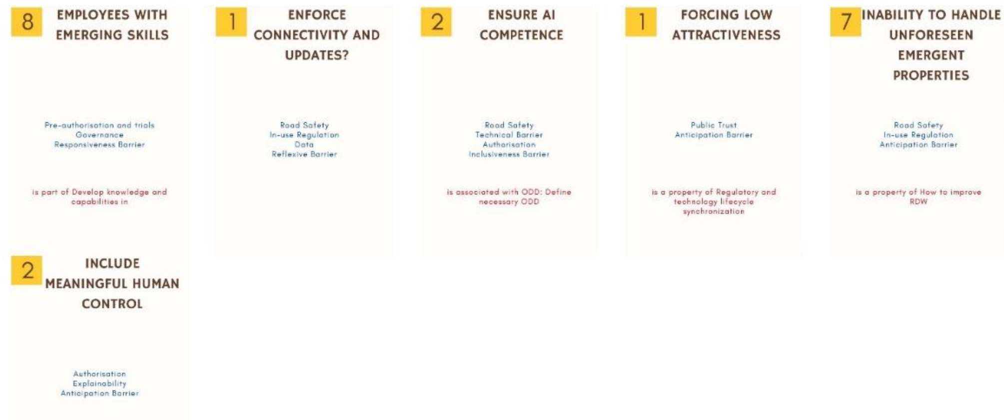

Figure 28: Open, axial and selective code cards - Part 5

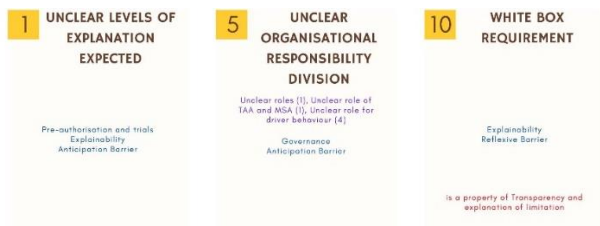

Figure 29: Open, axial and selective code cards - Part 6

Ability to swift recalls

is a property of Lack of agility

In-use Regulation / Public Trust / Response and Change / Responsiveness Barrier

3: And we are because we are in that transition period at the moment and for the sake of public trust it needs to be immediate and not piece meal. And I think there are some concerns at the moment that Nitza has with Tesla and I don't know any details but that there are investigating and that kind of investigation gets here to the media and then that is detrimental for public trust and acceptance of the service. So in terms of that sort of responsiveness barrier, you need the manufacturer, the supply chain or the supply chain manufacturer, and you authorize driving entity communication to be so seamless and the onus on the Ade to react in a very timely fashion even if it means loss of revenue and reputation.

And when an incident is coming you need to be reactive or responsive quite quickly. That's I don't need to wait for two months studying now. You need to act immediately. Can we do it? I don't know. OK, I doubt it. But those questions can be seen as barriers. That is a big barrier for sure organizational capability.

For instance, if our organization creates a certain boundary setting within an open norm and applies it to various manufacturers handing out multiple type approvals and then after a few years the setting is found to be wrong, this has a huge impact on the job manufacturers and end customers. As an administrative body, the legislation requires us to act upon it and prioritize safety and precaution for the people.

Adapting software self-certification

Is a solution of Lack of agility

Governance / In-use Regulation / Reflexive Barrier

2: Going to especially if you talk about artificial intelligence so no way we can control it. Maybe that should be a part of self-certification.

Onus is on the manufacturer to self-certify and I don't think self-certification. Well, we've seen this with the US with Boeing with the 737 Max, the self-certification process for airworthiness is difficult and we don't have self-certification in the same way in Europe. So there's an issue.

Adaptation to local driving behaviour

is associated with Address road user diversity

Anticipation Barrier / Inclusiveness Barrier / Pre-authorisation and trials / Road Safety

Figure 30: A sample page of the codebook

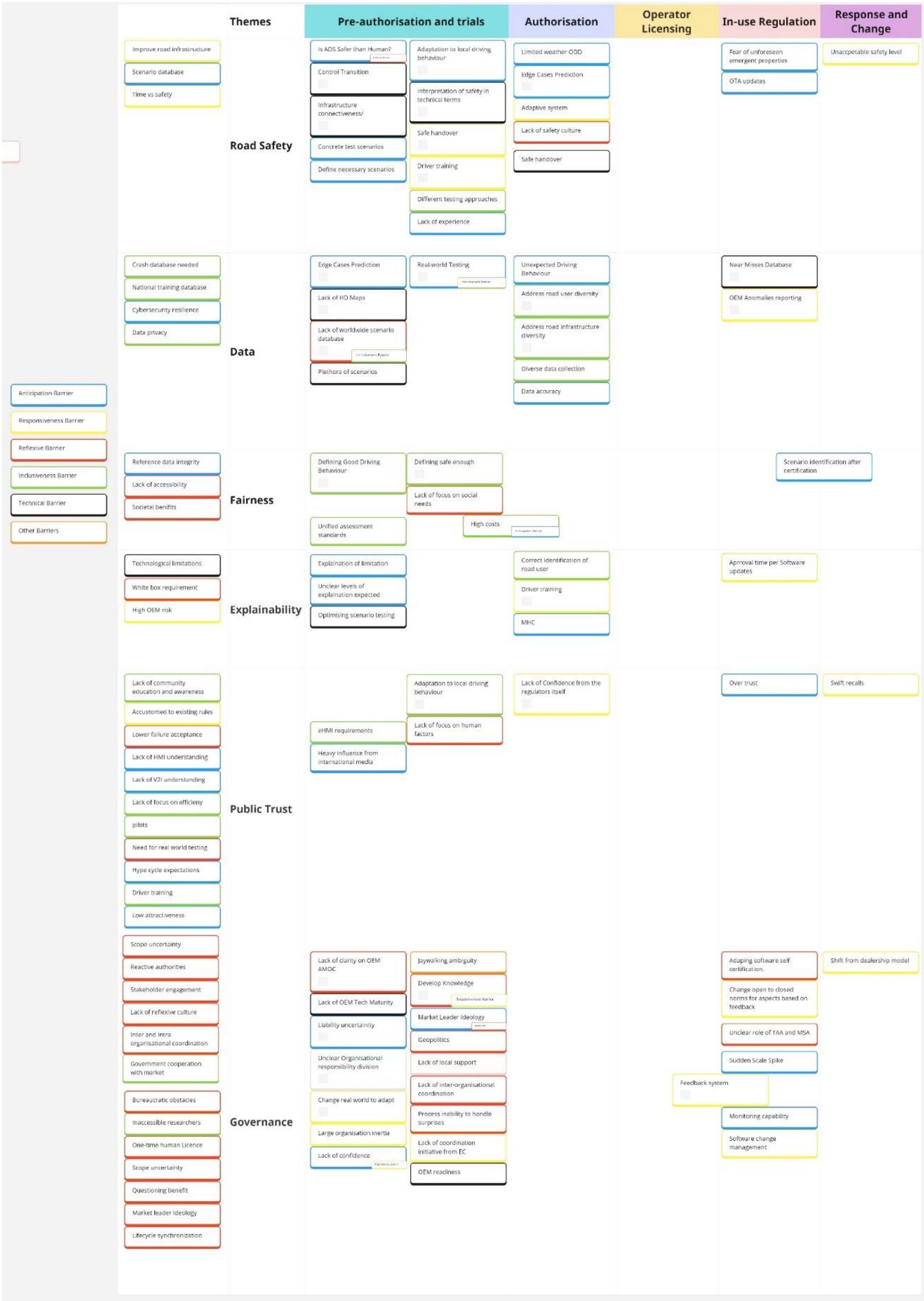

Figure 31: Barrier-lifecycle matrix filled with open, axial and selective codes provided for better understanding

Outcomes from the feedback session

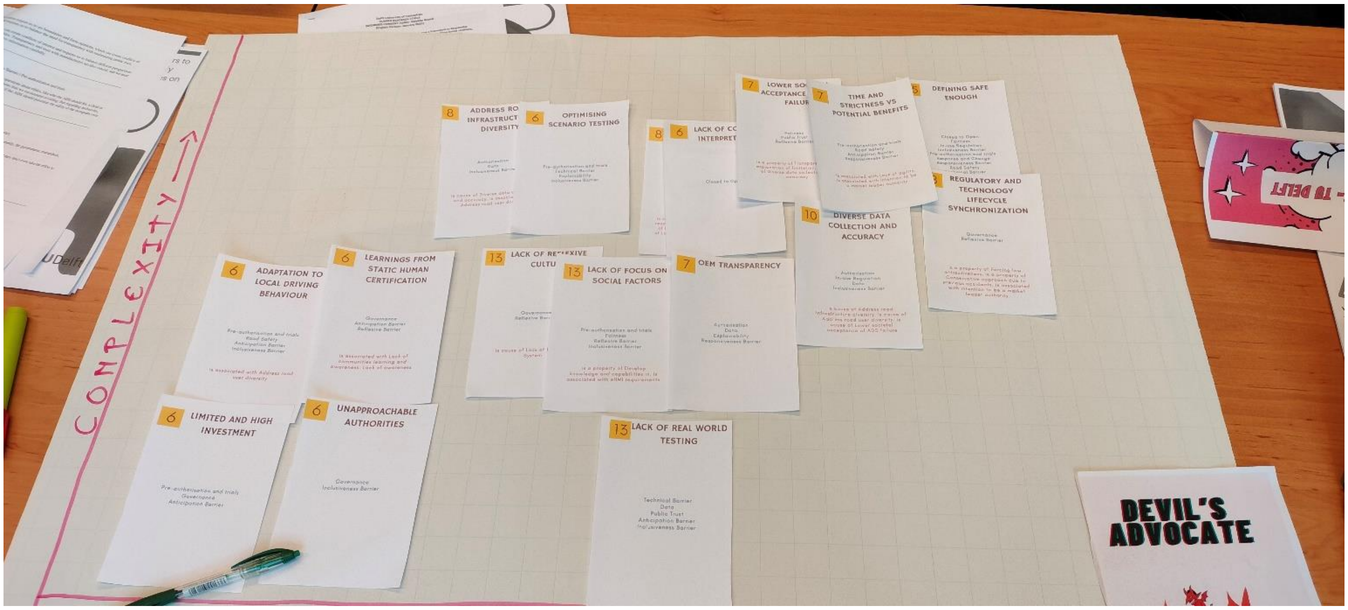

Figure 32: Severity-Complexity sequencing - Part 1

Figure 33: Severity-Complexity sequencing - Part 2

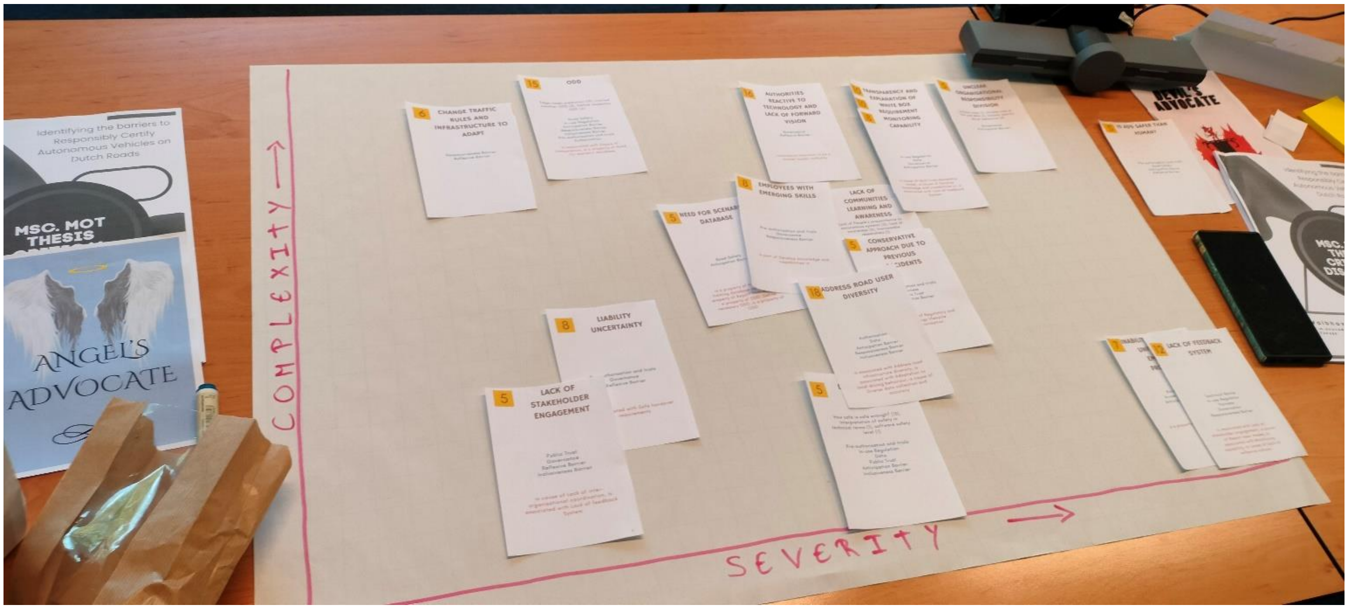

Figure 34: Severity-Complexity sequencing - Part 3

Appendix E

Codebook

Table 12: Selective code: Lack of inter-organisational coordination

Axial code	Open code	Barrier description	Sample quote	Groundedness	Participants
Lack of European harmonisation		Lack of harmonised approaches due to the economic diversity of MS causes inconsistent progress in adopting ADS technology and delays mutual recognition of certifications	"Yeah, you have the aspect, probably that some countries might be more advanced than other countries and road infrastructure. So if you drive over the border, so unification of certification rules might also be an important aspect." -GDD	10	GAR, NAP, UDA, GDD, NEC, NAT, NMR, NAR3
	Different pace of development	European countries are progressing at different speeds in ADS development and regulation, with only a few leading while others wait, slowing overall harmonisation and lagging behind non-EU countries.	"And I think one of the obstacles is that there are only three or four countries in Europe developing it, and the rest are just waiting. What's going to happen?" -GAR	4	GMR, GAR, NAA
	Difference in risk appetite	The question of "How safe is safe enough?" differs across countries, influenced by past decisions and political inclinations, creating a matrix of standards shaped by each nation's unique contexts and complicating a universal safety baseline.	"Yeah. What's how safe is safe enough? This political question translated into country-dependent thresholds. Not one figure, but a whole matrix of standards." -EAR	2	EAR, NAR3
	Lack of coordination initiative from EC	The transition from closed to open norms approach lacks a top-down approach led by the EC or UNECE to establish a supranational authority, harmonising interpretations as only they have the resources to do it. Initiation should be with developing a more harmonised documentation aiding interpretation and implementation materials.	"Multiple type approval authorities need to agree, which is not efficient and costs a lot of time. The European Commission needs to direct this process." -NAP	6	NAP, EMS, NAR, NAR2
	Competitive authorities	National type-approval authorities operate independently across the continent. authorities compete for OEMs by prioritising appeal over uniform safety standards to secure certifications impacting regulatory rigour and quality standard implementation and this environment requires new approaches that emphasise cooperation rather than competition.	"Authorities are also competitors a bit, but an OEM needs to have a certificate in hand to bring a vehicle to the European market. KBA can give it, or UTAC can give it, and then an authority can make itself more appealing, which creates competition." -EAR	2	EAR, NEC

Axial code	Open code	Barrier description	Sample quote	Groundedness	Participants
Unclear organisational responsibility division		Vehicle technology now relies heavily on environmental sensors and digital information, which necessitates a shared responsibility between traditionally separate silos like road builders and automotive manufacturers.	"It isn't legislation, but you really need to look at it, so it needs to be much clearer that the mandate is about who's responsible for acting on it. You need to know whether it's market surveillance authorities or type-approval authorities in the Netherlands or Europe." -NAR	6	GAR, NAP, GDD, GIT, NAR2
	Unclear role for driver behaviour	As vehicle automation increases, there is uncertainty over who will regulate the interaction between ADS and human drivers.	"We get not only to look at the vehicle from a technical perspective but we should also look at the vehicle from a driving behaviour perspective." -NMR	2	NCD, NMR
	Interdependency between vehicle and infrastructure	Vehicle and infrastructure technologies are becoming more interconnected, and future certification processes must consider both.	"There is a big dependency between the car and the road infrastructure in future because other systems rely on what I see in the environment. Usually that's done by the eyes and neural nets of the person itself of the driver. But now the technology has to take off the sensors and the digital information that you can get and what is seen by the environment. So there's a shared responsibility." -GDD	1	GDD
Lack of shared understanding		Knowledge gap between technology providers (OEMs, tier-one suppliers) and the regulatory bodies overseeing them, coupled with inconsistent enforcement of standards among certification bodies leads to operational inefficiencies and innovation delays.	"From a technology point of view, if you have experience in assessing a vehicle, architecture, sensor, or whatever, you can use that experience to educate your colleagues in other certification bodies." - NAR2	13	EIN, UPA, EAR, NAP2, NEC, NMR, NAR2, EPA, NAR3
			Total	46	

Table 13: Selective Code: Defining Safe Driving

Axial code	Open code	Barrier description	Sample quote	Groundedness	Participants
How safe is safe enough?		A standard of safety acceptable for public use is needed, but without precise and universally accepted definitions creates significant obstacles to certification as regulators, OEMs, and the public all need a clear benchmark to assess the safety of ADS.	"The question of when it is sufficiently safe is complex and varies depending on who you ask. Often, the safety threshold either rises or falls over time". -EAR	11	GMR, NAP, NAL, EIN, EAR, NAR

Axial code	Open code	Barrier description	Sample quote	Groundedness	Participants
	Risk framework complexities	Different perspectives on risk acceptance are present, each with distinct social and ethical implications but developing and agreeing on a solution is not straightforward.	"Netherlands need to agree on a risk framework based on our risk appetite" -NAR3	5	EAR, NMR, NAR3
	Interpretation of safety in technical terms	The barrier lies in the difficulty of interpreting and quantifying "competent driving" in technical terms, which creates challenges for standardising and regulating ADS.	"Because if you want safe traffic, you cannot describe that in technical terms. Safety is not something that is an exact number" –GAR	9	NAL, EIN, GAR, EAR, NAR
Is ADS safer than humans?		While ADS can potentially reduce accidents caused by human error, their ability to interact safely with other road users and handle unpredictable situations remains uncertain. A key societal question remains whether ADS certification should depend on its current ability to outperform human drivers or if it should focus on the potential for saving more lives in the long term.	"I think it's really the discussion is if you got autonomous vehicles, do you accept that there will still be accidents happening? Or are you from the school that is thinking well, an autonomous vehicle can't make an accident and should never be involved in an accident? That's not gonna happen. So how to assess a vehicle that it's better than a human driver?" –GMR	9	GMR, EMS, NCD, GIT, NAA, NEC
	Defining a baseline driver	Defining a baseline driver for ADS involves establishing a standard that reflects competent and safe driving behaviour, which is challenging due to the variability in human driving performance.	"Human drivers, especially young ones, make more accidents after getting their license, meaning what they show in exams is not the same as real driving. We see the same problem with vehicle manufacturers." -NCD	9	GMR, NAR, NCD, UDA, NAL, EIN
Assessing maturity of judgment		Human drivers rely on intuition and judgment honed through experience, while ADS are restricted to the data they have been trained on, limiting their ability to handle entirely novel situations.	"the real challenge is ensuring ADS can manage these unknown unknowns" -NCD	2	NCD, UPA
			Total	45	

Table 14: Selective Code: Improve societal stakeholder's engagement and education

Axial code	Open code	Barrier description	Sample quote	Groundedness	Participants
Lack of mandatory inclusion		Without mandatory inclusion, key stakeholders are not involved in shaping regulations, which can lead to biased safety assessments and decisions that fail to account for all road users' needs and concerns.	"We need road authorities, city representatives, and different user Organisations to be part of the approval process." -EMS	13	NAR, GMR, GAR, EMS, NCD, UDA, EIN, NAT, SCI

Axial code	Open code	Barrier description	Sample quote	Groundedness	Participants
Societal awareness and acquaintance		Educating the public about ADS capabilities, limitations, and operational changes is essential to mitigate risks, prevent misunderstandings, and build trust, given the changes to driving dynamics and traffic interactions.			
	Societal awareness	Limited public awareness and a lack of proactive communication about ADS advancements lead to resistance, misuse, and hesitancy to accept new technologies due to insufficient proof of safety and reliability. Establishing dedicated oversight bodies or review mechanisms could enhance public trust by ensuring that ADS updates are scrutinized before widespread deployment.	"The most important thing is making sure the public knows what's happening. In terms of inclusivity, it's about participation of all stakeholders. Most road projects include stakeholders who are aware of what needs to be done." -NAR	9	NAR, UDA, UPA, EIN, NAP2, NEC
	Societal acquaintance	Aids societal understanding, which helps build public trust. Gradual deployment of partial to fully autonomous systems within public spaces can lead to an increase in societal interaction and aid regulators' understanding.	"Singapore got autonomous dustbins driving around in the center of the city to get the people acquainted with something autonomous." -Anonymous	3	GMR, GDD, NAL
	Mixed traffic	The lack of focus on the transition phase with ADS introduction and its effects on traffic behaviour is highlighted.	"Mixed traffic situations with old and new cars need attention; new generation cars with ADS will expose a different behavior, which might create more traffic jams." -GDD	1	GDD
End-user training		End-users need thorough training or information about the limitations of their vehicle's automation capabilities. Without clear and timely education, drivers may struggle to understand what their vehicle can and cannot do, which is required for operations like handover when necessary.	"I do see a necessity to have correct messaging and explanation of the risks associated with it."	4	GAR, NAL
	Explanation of limitation	By ensuring that both the functional scope and the potential risks associated with ADS are communicated, end-users' preparedness can be improved.	"OK, in any way, written, shape, form, whatever it needs, the driver has to be trained or informed in time about the limitations of the vehicle with the limit." -GAR	3	GAR, NAL, UDA
Lack of transparent decision-making		Clear and justifiable explanations of decisions can aid technical standards and address the multiple layers of responsibility and administrative complexity involved in the approval process.	"The open norms require us to set boundaries and form opinions, which can take years for everyone to feel comfortable with. The main issue is documenting and explaining our decisions clearly." -NAP2	6	NAP2, NME, SCI, NCD
			Total	39	

Table 15: Selective Code: Regulatory and technology lifecycle synchronization

Axial code	Open code	Barrier description	Sample quote	Groundedness	Participants
Lifecycle dynamics of regulation and technology		Highlights the slow regulatory process and its misalignment with rapidly advancing technology, creating a need for faster adaptation to ensure regulations don't lag behind innovations.	"From a technical point of view, regulation should be more in line with technology innovation, but this is difficult because the life cycles of both are quite different. The life cycle to get a regulation is very long, but it is important to adapt." -GDD	20	GMR, GAR, NAP, EMS, NAR, GDD, EIN, UPA, EAR, NAT, NAR, NMR, NAR2
	Reactive authorities lacking forward vision	Organisational inertia within regulatory bodies prevents them from acknowledging unconventional approaches. This resistance not only slows down the process of regulatory adaptation but also hampers the ability of large Organisations to foster an environment conducive to technological progress.	"The government should be more involved in stimulating development, not just observing. We need to build our own systems rather than relying on AI from other countries. Sitting back because of fear is not a good strategy." -NCD	9	GAR, EMS, NAR, NCD, NAR2, NAP2
Strictness vs innovation		Strict regulations designed to ensure safety often create rigid frameworks that limit the space for innovation. In areas like ADS, conservative regulations may slow down technological advancements that could improve safety and efficiency in the long term.	"Being too conservative hinders innovation. It will gain more than it loses. While human lives are at stake, which justifies caution, sometimes you need to take calculated risks to stimulate innovation." -NAL	10	NAL, UDA, UPA, EAR, NAP2, NMR
			Total	39	

Table 16: Selective Code: Optimising in-use data monitoring

Axial code	Open code	Barrier description	Sample quote	Groundedness	Participants
Monitoring efficiency		ADS certification requires robust real-time monitoring systems to compensate for knowledge gaps and ensure safety by tracking system performance and responsiveness. The current lack of capabilities and knowledge to manage the increased	"Responsiveness is crucial, and it involves in-service monitoring and feedback. The challenge is defining what needs to be reported and ensuring transparency from OEMs. The OEMs get a lot of information, but what do they need to report to TAA? This needs to be clear to ensure that necessary updates are made." –EIN	9	EMS, NCD, EIN, NAR2, NMR, NAR

Axial code	Open code	Barrier description	Sample quote	Groundedness	Participants
		responsibility of continuous monitoring is a barrier.			
	Quality assurance	The existing data standards are insufficient to ensure the breadth and depth of data needed for reliable ADS performance in real-world conditions. There are no strong compliance requirements to push OEMs to demonstrate that their systems are consistently reliable.	"The data should be certified too if I have a use case and I expect certain quality of the data, the digital data on accuracy or mainly on reliability, that is of course important. Yeah, before you can automate the car, you also the data that you use should have a stamp. This is usable for this type of use cases or not." –GDD	8	EIN, GDD, NAA, GMR, GAR, EIN, NAR
Near miss and crash database needed		Crash databases can map causal relations, improve practices, and adapt strategies to prevent repetitive incidents. Near-miss databases can aid proactive safety practices.		12	GMR, NCD, GIT, NAA, EIN, NMR, NAR2
OEM transparency		A lack of transparency from OEMs hinders effective oversight and risk management. Sharing data openly can improve safety and reduce liability risks but must be balanced with protecting proprietary information.	"A big barrier is transparency. You really need to be transparent. When there is something happening, otherwise we will never be able to act on certain things for the future. So we need to have a really good system for on-service monitoring." –NAR	10	NCD, GIT, NAA, NAP2
			Total	39	

Table 17: Selective Code: Optimise ODC governance

Axial code	Open code	Barrier description	Sample quote	Groundedness	Participants
Optimise ODC and scenario testing		The challenge lies in ensuring that ADS systems are evaluated across a broad but relevant range of conditions. Optimisation involves balancing thorough testing with the need for efficiency and practicality in the certification process.			

	Scenario overload	The sheer number of potential driving scenarios creates an overload that requires prioritising the most critical scenarios without neglecting the certification's rigour.	"How can you assess the amount of scenarios? If the OEM says these are the scenarios they did, how can you assess that's a good representation of what the car will encounter?" -EIN	7	GMR, UDA, EIN, NAA
	Improve scenario testing	Current testing procedures are resource-intensive and fail to bridge the semantic gap between simulated scenarios and real-world conditions.	"We use simulations, but they are not always applicable to real-life scenarios. Manufacturers focus on what they want to prove, so how does it transfer to reality?" –NCD	8	NCD, EMS, NAA, EIN, GDD, GIT
	Multi-stage testing	There is a need to define a testing approach that progressively assesses performance from simple scenarios to more complex environments.	"You have to make sure that all the tests have been done correctly. I like the multi-pillar approach: first simulation, then proving ground, then public roads, and finally deploy." –GMR	3	GMR, UDA
ODD Limitations		The challenge is creating a clear boundary for where the ADS can safely operate, while ensuring it can adapt or transition safely when approaching the limits of its ODD, particularly in changing conditions.	"So that we don't get to a position where we're approaching a cliff edge of falling outside of our ODD, we have more of an elastic bubble" -UDA	2	UDA, EAR
	Weather impact	Ensuring that ADS can operate safely across diverse and unpredictable environments adds complexity to defining and validating the full scope of its ODD.	"You have the environment so you know the weather. Is it snowy? Is it foggy? Is it rainy? And that affects what sensors you use. Cameras, lidar, radar all react differently to weather." -UDA	1	UDA
	Edge case	These low-frequency but high-impact situations are difficult to predict and test, making their management vital for ensuring overall system safety.	"Understanding how an ADS will handle edge cases—rare or unexpected scenarios—is crucial. Edge cases can be particularly challenging to predict and test for, and ensuring the ADS can handle these effectively is a significant part of the anticipation process." –EIN	3	GAR, GDD, EIN
Need for scenario database		By pooling data across countries and manufacturers, this database could provide a consistent foundation for ADS testing. The absence is slowing the process and compromising safety and certainty.	"That's why I think it's important to have worldwide kind of...a scenario database where all those stakeholders in different countries are involved." –GMR	10	NAP, GMR, GDD, GIT, NAA, EIN, NEC, NAT
			Total	34	

Table 18: Selective Code: Normative shifts with open norms

Axial code	Open code	Barrier description	Sample quote	Groundedness	Participants
Interpretation ambiguity		Open norms lack criteria clarity leading to varied interpretation. This inconsistency can create confusion about compliance and undermine trust in the certification process.	"In a system with fixed norms, if a number is wrong, it can be changed in the legislation. With open norms, we are responsible for setting and adjusting boundaries based on new insights." -NAP2	7	EMS, NAP2, GIT, NAT, NAA
	Flexibility vs consistency	Maintaining consistency requires regulators to align new interpretations with previous ones. As responsibilities decentralize, regulatory bodies must regularly coordinate to ensure these interpretations do not diverge to avoid discrepancies in how safety standards are applied across Europe.	"The number of tests needs to be reduced to a satisfactory level. So that's being open and it's up to the technical service and the authority to determine what is that satisfactory level." -GIT	8	EMS, NAL, GIT, NAR2, NAP
	Practical impediments: Decentralised responsibility	The decentralisation of regulatory responsibility can force each type approval authority to make their own interpretation which they are not used to currently.	"So whereas the vehicle before was or we just did a once approval at start but now as software is changing and as it's new technology, we do we have regulation but we have a bit open norms. So we have to start to make interpretations. The responsibility is pushed by the regulators now to Organisations like RDW." -NMR	6	NMR, NAP, EAR, GIT
Shift to system validation		The transition from component-specific safety testing or individual systems, to whole-vehicle validation might require a more holistic approach that goes beyond traditional methods.	"Or maybe in sort of overall view? Because also our discussion is about basically the vehicles, but vehicles are part of a whole system. You also got infrastructure. The behavioural aspects also there's other modalities on the roads, cyclists, etc. If you look at it as a whole system, I think you could also improve Product Safety as a whole." -EAR	3	GMR, EMS, EAR
	Complex testing	System validation would require resources to test across dynamic, real-world scenarios, a challenge that current regulatory bodies are not fully equipped to handle.	"Safety of the design. So the whole design needs to be safe. And how are you gonna judge design? It's not like measuring and then it's safe, so that is a very big challenge.""Safety of the design. So the whole design needs to be safe. And how are you gonna judge design? It's not like measuring and then it's safe, so that is a very big challenge." -EIN	1	EIN
Reduced reliance on regulation		Open norms can force OEMs and regulatory bodies to interpret rather than rely on predefined rules, which can lead to legal ambiguity.	"With a small description of how it was done in the past. In the past, we had a proper description of the boundaries and thresholds of the technical tests that had to be performed on cars. So for example, when a car needs to have a brake and when it needs to get to a standstill it must brake within certain meters per second. So these values were very clear. Of course this is not really applicable to open norms." -NAR2	2	NAP, NAR2

Axial code	Open code	Barrier description	Sample quote	Groundedness	Participants
	Uncertainty in compliance	OEMs can face uncertainty in knowing if their systems meet the required standards, which can stifle innovation.	"Kind of strategies to make sure that when we have a rule, the OEM doesn't only comply with the rule but it's also compliant to the whole behaviour of the vehicle. It's not only about meeting the requirement, it's more or less about, do I have a safe vehicle?" -NAR	2	NEC, NAR
			Total	29	

Table 19: Selective Code: Develop internal capabilities

Axial code	Open code	Barrier description	Sample quote	Groundedness	Participants
Regulators with emerging skills		Emphasises the need for building processes required to certify ADS and restructuring Organisations to better handle emerging technologies.	"Bring more people inside RDW who can advise, work in cooperation with other companies and authorities. We need new people with the required skills ASAP." -GAR	25	GMR, GAR, NAP, NAR, UDA, GDD, GIT, NAR2, NMR, NCD, EAR
Lack of knowledge communities		Limits the exchange of insights between regulators and industry, leading to fragmented understanding and slowing the adaptation of new technologies.	"We are trying to create learning communities to speed up the commercial use of autonomous vehicles." -NCD	3	NCD, GDD
			Total	28	

Table 20: Axial code: Lack of real-world testing

Open code	Barrier description	Sample quote	Ground-edness	Participants
Need for real-world testing	Governments are hesitant to expose the public to untested, potentially unsafe technology, creating a tension between ensuring public safety and the need to trial systems in real-world conditions. Without it, development remains theoretical, delaying the progress needed to make the technology safe for public use.	"Testing in the real world is crucial. Digital testing can't cover all possible situations. It's important to test in real situations to understand what can happen." -NAR	15	GDD, NMR, GAR, UPA, UDA, NAA, NAR, NCD

Government investment in test areas	Governments are capable of establishing large-scale test beds that can accommodate multiple ADS developers. However, investment in such infrastructure is currently limited, hindering the ability to conduct real world testing.	"It would require, let's say, a lot of test areas. Yeah, some things you cannot do on the road. So I think the government should invest in test areas that you can use to test your new technology before you go on to the road." -GDD	3	GDD
		Total	18	