University of Stavanger
Stavanger, 2023

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Autonomous Vehicles in Road Tunnels : A Risk Safety Perspective

Master Thesis, 2023

Master of Risk Management

University of Stavanger

Acknowledgements

I would like to pay my gratitude to my supervisor **Prof. Henrik Bjelland** who remained the ultimate solution to every problem I have had during this process. He made sense of every confusion and provided with the valuable insights on and off the topic and made it an all-learning process throughout.

I would dedicate this work to my beloved mother whose prayers and faith in me have been the biggest strength of my life. I am grateful to my friends for their valuable comments, inputs and insights throughout this work.

I humbly present this work for evaluation and insightful comments from the teachers.

Department of Safety, Economics & Planning

Stavanger, June 2023

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Abstract

This study examines the challenges associated with deploying autonomous vehicles (AVs) in road tunnels, focusing on both operational aspects and vehicle-human interaction. This work explored that road tunnels present unique constraints, such as limited visibility and confined spaces, which necessitate careful consideration for AV integration. It is observed that factors like varying light conditions and restricted communication capabilities within tunnels impact AVs' performance. Additionally, the study investigates and categorizes challenges related to tunnel geometries, infrastructure modifications, sensor technologies, emergency situations, and human-machine interaction.

Furthermore, this work comprehensively explored academic and non-academic literature, gathering contemporary knowledge on AVs in road tunnels in one place to provide a foundational base for researchers on this topic. In this regard, the adopted methodological framework is also presented for researchers' review. The other notable contribution is to specifically highlight the critical operational issues of human-AV interaction in tunnel environments. In the last section, it also proposes potential solutions to these issues. In doing so, it keeps the directional approach open for other researchers as there are insightful risk-related implications for further research in this significant domain.

Keywords – Autonomous Vehicles, Road Tunnels, Risk Perception, Human Behaviour.

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1 Introduction

1.1 The Objective of this Study

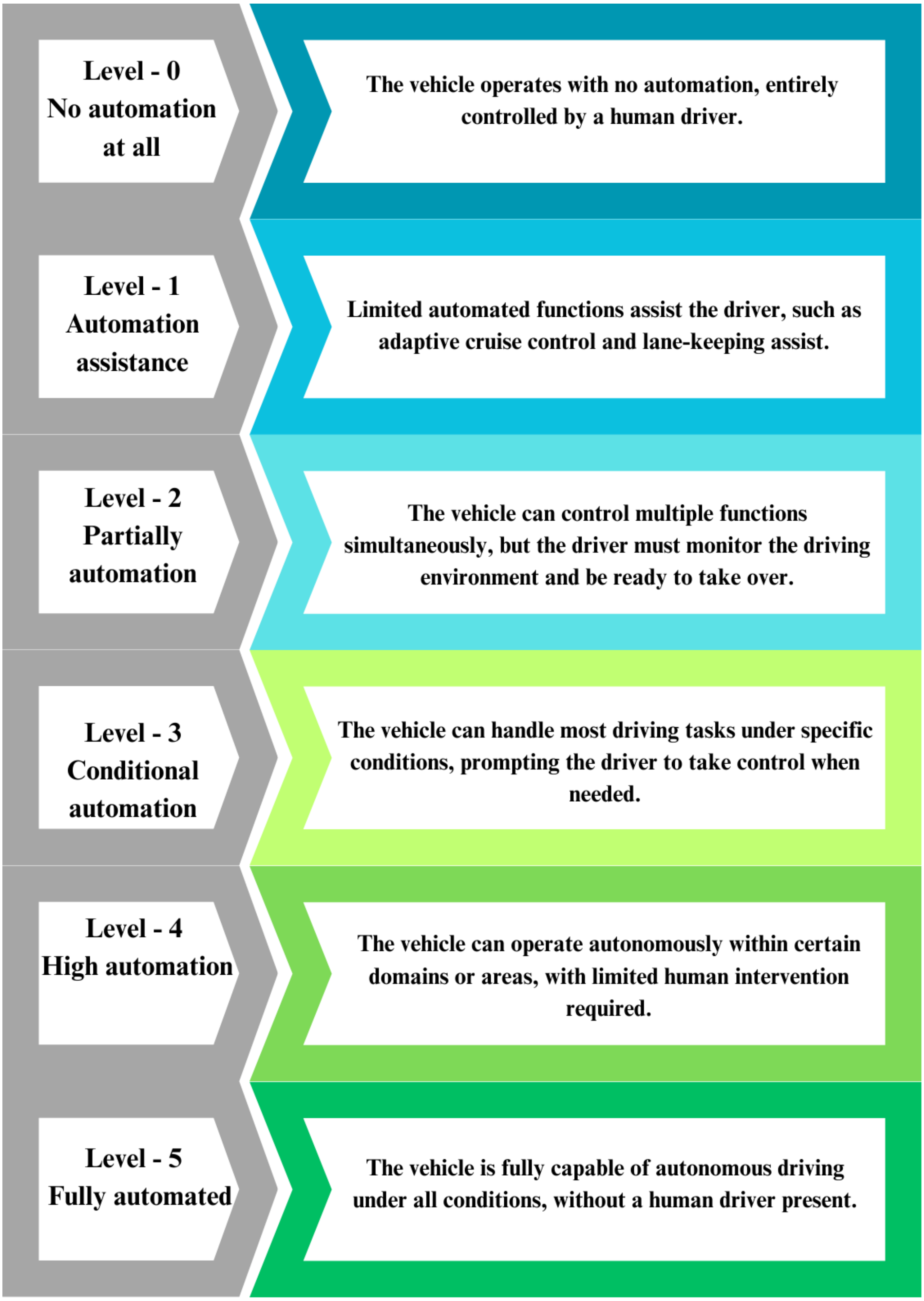
Autonomous vehicles (AVs), a prominent technological advancement in the transportation industry, have garnered significant attention and research interest in recent years. These vehicles possess the capability to operate and navigate without human intervention, relying on advanced sensors, artificial intelligence, and communication systems. The emergence of AVs holds immense potential to revolutionize various aspects of transportation, including safety, efficiency, and mobility. However, their widespread adoption and deployment necessitate comprehensive understanding, analysis, and research to address associated challenges and ensure seamless integration into existing infrastructure.

This academic exploration delves into the multifaceted realm of AVs, examining their technological advancements, societal implications, regulatory frameworks, and the need for further research to unlock their full potential (Liu et al., 2021).

AVs, also known as self-driving cars which are driven without any human assistance, by using a combination of sensors, control systems, and artificial intelligence algorithms to navigate roads and highways. Society of Automotive Engineers (SAE)[1] has introduced different autonomy levels also known as Society of Automotive Engineers levels, which are a set of standardized definitions for the different levels of automation in vehicles. That goes from level - 0 where vehicles are fully driven by humans to level - 5 where human intervention is not needed in all conditions (Taxonomy, 2016). As illustrated below:

[1]SAE is the leading body in the world for connecting and educating mobility professionals for conducting safe, green, and accessible mobility solutions. It comprises 128,000 professionals connected at one platform in the industries of Aerospace, Automotive and Commercial vehicles. The aim is to enable learning in the field, and standards development with the ultimate objective to produce collaboration across borders toward diversity, equity and inclusion (URL: https://www.sae.org/)

Figure 1.1: Autonomy Levels of SAE



Here is an overview of the development and working of AVs:

Development: The development of AVs involves a multi-disciplinary approach, with experts in mechanical engineering, electrical engineering, computer science, technical safety, and other fields working together to design and build the necessary hardware and software components.

Sensors: AVs rely on a variety of sensors to gather information about their surroundings, including different kinds of cameras, liDAR, radar, and ultrasonic sensors. These sensors provide the vehicle's control system with a continuous stream of data about nearby objects, other vehicles, pedestrians, roads, and weather conditions as explained by Braid et al. (2006) and then followed by Arnold et al. (2019).

Control System: The control system of an autonomous vehicle processes the data from the sensors, makes decisions about the vehicle's actions, and executes those actions. The control system uses advanced algorithms to analyze the sensor data and make decisions about the vehicle's speed, direction, and acceleration (Maurer et al., 2016).

Artificial Intelligence: AVs use AI algorithms to make decisions about vehicle actions based on sensor data and other inputs. These algorithms use machine learning techniques to analyze patterns in the data and learn from previous experiences, allowing the vehicle to operate safely and effectively in a wide range of scenarios (Zhou et al., 2020).

In mapping and localization: AVs are able to accurately locate themselves within their environment and navigate to their destination. This requires high-precision mapping and localization systems, as well as algorithms that can navigate the vehicle through complex environments like work zones or accidental areas (Madadi et al., 2021).

Communication and connectivity: For AVs communication and connectivity are the most important factors to communicate with other vehicles V2V and with surrounding infrastructure V2X, such as traffic lights and road signs, to navigate safely and efficiently. This requires resilient and secure communication systems that can handle large amounts of data (Bowers et al., 2016).

Human Factors: Even though AVs are designed to be self-driving, they may still require human input in certain situations, such as emergencies or unusual traffic scenarios. AVs must be designed with intuitive and easy-to-use user interfaces and control systems that allow for safe human intervention if needed (Feldhütter et al., 2016) and (Rödel et al., 2014).

Testing and validation: Finally, AVs must be extensively tested and validated to ensure that they are safe and reliable in real-world conditions. This involves testing the systems in a variety of scenarios, using simulation tools to predict how the systems will perform in new and untested situations, and collecting data from real-world testing to refine and improve the systems over time.

AVs are the future of transportation, and sensors are at the heart of this technology. AI algorithms, cameras, LiDAR, radar, and ultrasonic sensors all play an important role in enabling AVs to navigate their surroundings and make decisions (Maurer et al., 2016). As technology continues to evolve, we can expect to see even more advanced sensors and technologies being developed to make our roads safer and more efficient.

AVs have the potential to revolutionize transportation in road tunnels. With their advanced sensors and computing capabilities, AVs can safely navigate the tunnels and reduce the risk of accidents caused by human error. Some potential benefits of using AVs in road tunnels include improved safety, increased efficiency, reduced emissions, and improved accessibility, AVs can provide mobility options for people with disabilities, who may face challenges navigating the tunnels safely and independently (Faber and Van Lierop, 2020).

1.2 Challenges

However, there are also technical and regulatory challenges that must be addressed before AVs can be safely deployed in road tunnels. AVs represent a significant engineering challenge, requiring the development of sophisticated sensor fusion, safety, cybersecurity, legal and regulatory, and public acceptance mechanisms. However, these challenges can be overcome through collaboration between engineers, policymakers, regulators, and the public. With continued innovation and investment, AVs have the potential to transform transportation and improve road safety and efficiency.

Following is the scheme of this work, in the next section literature study, has been concluded to identify the challenges for AVs in Road Tunnels with a special emphasis on unexplored (lesser explored) areas of automation level 4 or above vehicles in road tunnels that provide the basis for this thesis. Later, detailed coverage has been done for challenges and their potential solutions identified within and outside academia. In the following section, narrowing down the work further to Human Behavioural aspects, challenges and potential solutions are explored which follows the conclusion and final word by the author.

2 Literature Review and Methodology

2.1 Methodology

This study employs a comprehensive methodology to investigate the various aspects of autonomous vehicles (AVs) related to risk safety factors in road tunnels. It includes the literature review as well as an exploration of non-academic material produced related to AVs in contemporary times. In doing so, the cogent purpose remained to keep the focus on producing some directional output for future research along with encompassing the most crucial risk-related factors for AVs deployment in road tunnels. However, while doing so, it was learned that there is acute scarcity in academia related to AVs' integration in road tunnels, especially when it comes to operational risk.

The general literature found in this regard covers various aspects like technical capabilities, financial implications, legal and regulatory paradigms and operational aspects of AVs in road tunnels.

In the technical field of autonomous vehicles, the focus is on developing and improving the technical aspects that enable vehicles to operate autonomously. This includes research and development in areas such as perception (sensors and computer vision), decision-making algorithms, mapping and localization, vehicle control systems, and connectivity. Technical advancements aim to enhance the safety, reliability, and performance of autonomous vehicles.

The financial aspect of autonomous vehicles involves studying the economic implications and financial considerations associated with their development, deployment, and operation. This includes analyzing the cost-effectiveness of autonomous technologies, estimating the financial impact on industries and businesses, assessing the return on investment for autonomous vehicle projects, and exploring potential business models and revenue streams. Financial analysis helps stakeholders make informed decisions regarding the feasibility and sustainability of autonomous vehicle initiatives.

The legal and regulatory field of autonomous vehicles focuses on the legal frameworks, regulations, and policies that govern their use. This includes assessing the existing legal frameworks to identify gaps and challenges related to autonomous vehicles, addressing

liability issues in case of accidents or failures, ensuring data privacy and security, defining standards for vehicle safety and performance, and establishing rules for testing, certification, and deployment of autonomous vehicles. Legal and regulatory considerations play a crucial role in ensuring the safe and responsible integration of autonomous vehicles into society. Although the focus of this study is to cover technical aspects but a brief mention of prominent works related to financial and legal aspects has also been added.
Within the technical aspect, it has been further divided into two main categories such as the challenges of AVs on open roads, and in road tunnels but this study confines to the challenges AVs in road tunnels. In doing so, it focuses on three main categories of challenges: operational, scientific, and interactive.

Operational challenges involve ensuring the optimal functioning of sensors and the mechanical systems of vehicles in tunnel environments. This includes addressing issues such as sensor reliability, the robustness of vehicle components, and adaptation to unique tunnel conditions.
Scientific challenges pertain to the development and application of advanced artificial intelligence (AI) and machine learning algorithms to enhance the capabilities of autonomous vehicles in tunnel scenarios.
Interactive challenges revolve around the effective communication and interaction of autonomous vehicles with other vehicles (V2V), infrastructure (V2I), and human occupants (vehicle-to-human). These challenges include developing reliable communication protocols, addressing interoperability issues, and ensuring smooth coordination between different stakeholders in tunnel environments.

Finally, this study focuses on autonomous vehicle-to-human interaction within road tunnels, recognizing the significance of human behavior in the successful adoption and operation of autonomous vehicles. It examines the challenges associated with human acceptance, trust, and understanding of autonomous systems in tunnel environments. It proposes potential solutions to foster positive human-vehicle interaction, including the development of intuitive user interfaces, effective communication strategies, and comprehensive user education and training programs.

The below illustration depicts the graphical representation of the research methodology adopted in this work, starting from a broader research area to the specific aspect of vehicle-human interaction of AVs in road tunnels.

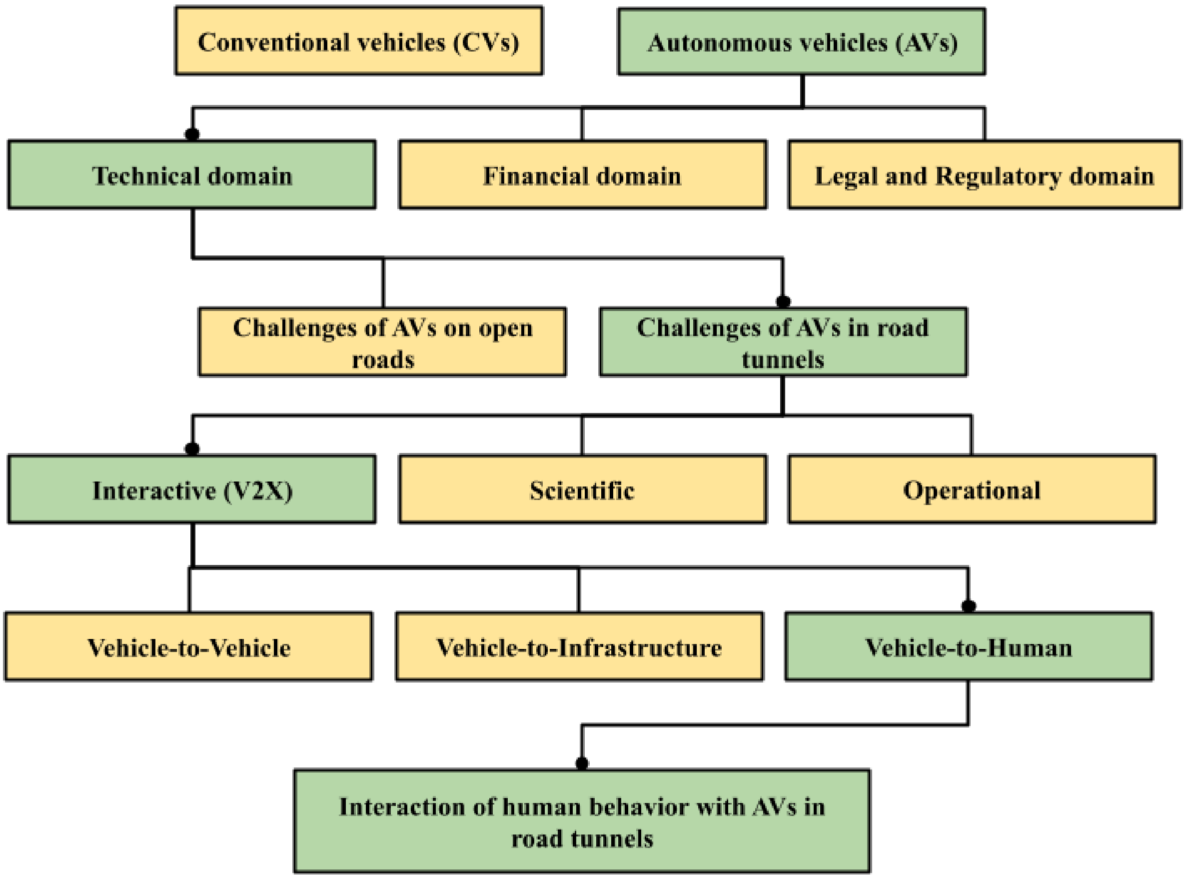


Figure 2.1: Research Methodology

2.2 Literature Review

The current literature on autonomous vehicles (AVs) highlights several compelling factors regarding their deployment. This section aims to present the strengths and challenges associated with the introduction of AVs. The strengths will be discussed first, followed by the challenges related to AVs in tunnels and on open roads, which will be addressed separately. The objective of this section is to provide a detailed literature study on established data on the topic of AVs in road tunnels. All the following points are derived from previously published articles and literature.

AVs have made significant advancements in improving safety and enhancing traffic and transportation flow. By reducing accidents caused by human error, which is currently a major contributor to road fatalities, AVs have the potential to make a substantial impact (Wang et al., 2020). Advanced sensors and algorithms enable these vehicles to have 360-degree perception, precise decision-making capabilities, and rapid response times, mitigating risks associated with human factors such as fatigue, distraction, and impaired driving. This improved safety aspect of AVs is crucial for their widespread adoption (Petrović et al., 2020).
Another factor that contributes to the adoption of AVs is their ability to optimize traffic flow. By employing coordinated algorithms and data exchange capabilities, AVs can navigate efficiently, avoid congestion, and optimize route planning (Maurer et al., 2016). This not only reduces travel times but also minimizes fuel consumption and greenhouse gas emissions. Additionally, the concept of shared mobility models and efficient transportation services can lead to a reduction in the number of vehicles on the road, further enhancing traffic flow and environmental sustainability as evidenced by Liu and Song (2019) and later by (Madadi et al., 2021).
Moreover, AVs hold great potential in enhancing mobility options for individuals with limited mobility, such as the elderly and disabled populations (Maurer et al., 2016). By providing safe and convenient transportation solutions, AVs empower individuals who currently rely on public transportation, specialized services, or assistance from others. This improved accessibility not only increases independence but also enhances the overall quality of life for those who face transportation barriers (Faber and Van Lierop, 2020).

As AVs become integrated into society, they can influence urban planning strategies. The reduction in parking requirements and changes in transportation demands brought about by AVs can lead to more efficient land use, optimized infrastructure planning, and enhanced urban design (Seo and Asakura, 2022). This integration presents opportunities for improving the overall functionality and sustainability of urban environments (Nadafianshahamabadi et al., 2021).

The introduction of AVs also has significant implications for economic growth. Increased productivity during commutes, reduced congestion, and optimized logistics operations can positively impact industries and businesses (Tengilimoglu et al., 2023a). Furthermore, the emergence of new jobs and opportunities in vehicle design, software development, and mobility services contribute to job creation and economic diversification (Montgomery et al., 2018).

AVs have the potential to transform transportation and offer numerous societal benefits. By leveraging advanced technology and addressing the challenges they entail, AVs can contribute to improved road safety, enhanced efficiency, increased accessibility, more sustainable mobility, and economic growth. Continued research, development, and collaboration across various sectors are essential to maximize the benefits of AVs while addressing the challenges associated with their widespread adoption. Numerous challenges arise when AVs encounter open roads and road tunnels. These encounters pose uncertain problems that AVs must confront, necessitating careful consideration and viable solutions. The following discussion highlights the challenges and feasible approaches that need to be implemented.

One significant challenge is the integration of artificial intelligence (AI) into vehicles (Abduljabbar et al., 2019). This involves addressing limitations and regulations, building public trust, managing high investment costs, fostering AI expertise, and addressing potential software malfunctions. Adhering to country-specific regulations, aligning road infrastructure, educating the public, securing the necessary funding, prioritizing training, and ensuring robust testing and fail-safe mechanisms are crucial steps in addressing these challenges (Meyer-Waarden and Cloarec, 2022).

Another specific challenge arises in the context of tunnel navigation for AVs. Scaling AI training for tunnel scenarios requires sufficient data and further research (Rao and Frtunikj, 2018). The reliability of AI algorithms in handling unexpected situations, accidents, and sensor malfunctions is also a critical aspect that needs to be addressed (Howard et al., 2017). Validating the performance and safety of AVs in tunnel environments through experiments is essential, and various methods have been proposed to tackle these challenges (Courbariaux et al., 2016) (Han et al., 2015).

The cybersecurity aspect of AVs is a significant concern. Cyber threats, including software hacking and misuse, can compromise the safety and security of AVs (Bezemskij et al., 2017). Hackers can exploit vulnerabilities in wireless systems, potentially gaining unauthorized access to vehicle data. Ensuring robust cybersecurity measures is essential to protect AVs from such threats (Malik and Sun, 2020).

Ensuring safety is a key challenge in implementing AVs. Technical errors in-vehicle technology can compromise safety such as the notable example of the Tesla autopilot crash in 2016, and establishing regulations that address the moral implications of accidents is challenging (Liu et al., 2021). Refining algorithms and gaining real-world experience will improve safety, but public acceptance and standardized safety protocols for AI-based AVs are still crucial aspects to consider (Taeihagh and Lim, 2019).

Operating AVs in road tunnels presents additional challenges, including work zones, and emergencies. Factors such as sluggish driving, road closures, unforeseen accidents, and sudden stops can hinder the smooth operation of AVs in tunnels. Overcoming these challenges requires careful planning, advanced algorithms, and efficient response mechanisms evidenced by Zang et al. (2019) and later by Hnewa and Radha (2021).

Connectivity challenges also arise in AVs, particularly concerning the utilization and control of sensor data. Vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communications enable efficient information exchange but raise concerns regarding location tracking and privacy breaches. Striking a balance between connectivity and privacy is a challenge that needs to be addressed to ensure the safe and responsible use of AVs as mentioned by Cui et al. (2019) after Bowers et al. (2016).

Road infrastructure is vital for everyday transport and the development of the automated industry. As vehicles advance and road networks expand, the demand for commercial vehicles and electric mobility increases. To ensure the successful deployment of automated vehicles, clear road markings, speed limit sensors, and well-maintained parking are crucial. This requires a combination of vehicle-mounted instruments and road-side digital infrastructure with sensors and internet connectivity (Liu et al., 2019).

Tunnel design significantly impacts the navigation and safety of autonomous vehicles (AVs). Challenges arise from factors such as narrow lanes, congestion, and sharp curves. The performance of AVs can be affected by high traffic and inappropriate driver behavior, emphasizing the importance of maintaining sufficient distance between vehicles to reduce stress (Kircher and Ahlstrom, 2012). Additionally, precision in the behavior of other vehicles becomes crucial for AVs' optimal functioning. Creating a calming driving environment in tunnels through appropriate colors, decorations, and designs can promote a sense of peace and enhance driver comfort (Qin et al., 2020). Moreover, tunnel lighting plays a significant role in AV safety and obstacle detection. Bright exits can cause temporary blindness, leading to potential hazards. To mitigate this stress, experts suggest incorporating artwork, conducting FMRI assessments, using specific lighting patterns, and playing slow music to enhance driver comfort and focus (Miller and Boyle, 2015) and later (Bassan, 2016).

Ethical issues in AVs impact human behavior, particularly in tunnel environments. When accidents occur, the vehicle must prioritize passenger and user safety, while considering the well-being of others, especially in collisions with lighter vehicles. However, ethical considerations vary depending on the situation and cannot be universally applied (Maurer et al., 2016). However, he further explained that an essential aspect to consider revolves around the ethical dilemmas that arise when an autonomous vehicle (AV) user is confronted with a traffic accident. In the event of a crash, split-second decisions determine whether the passenger or a pedestrian will be harmed. Surveys conducted on moral decision-making concerning AVs and road safety indicate that factors such as gender, nationality, and social status influence these judgments (Maurer et al., 2016).

Drivers pose challenges for AVs in tunnels through risky behavior such as tailgating, blocking, and aggressive actions (Soni et al., 2022). Negative attitudes towards AVs can lead to resistance and reckless driving, while overconfidence can result in a false sense of security (Rödel et al., 2014). Lack of trust may cause anxiety and erratic behavior, impacting safety in tunnels. Conversely, positive attitudes can promote cooperative driving. These factors highlight the importance of addressing human behavior to ensure safe interactions between autonomous and human-driven vehicles in tunnels (Feldhütter et al., 2016).

In addition to human interaction, AVs face challenges in communicating with drivers in tunnels. Drivers rely on gestures and speech, which are not easily understood by AVs. Misunderstandings can compromise road safety, especially regarding braking systems. Clear symbols and visual/audio cues can improve communication between AVs and pedestrians. Specific coding and signaling methods can be used for effective communication, such as short stops before crosswalks (Chen et al., 2015) (Stanciu et al., 2018).

As (Burns et al., 2013) has discussed that during emergencies in tunnels, drivers may panic and struggle to communicate with other vehicles, including autonomous ones. Effective methods include public announcement systems, illuminated lighting, and exit signage. Emergency alarm systems, sensors for detecting smoke and flames, and ventilation systems are crucial for occupant safety. Vehicle-mounted cameras can enhance situational awareness by detecting lane closures and redirection signs (Lee et al., 2022).

In the upcoming section, we will look into the challenges of AVs in road tunnels. These challenges, including human behavior, tunnel design, ethical considerations, risky behavior, lack of communication, and emergency situations, will be thoroughly examined and analyzed. Through empirical studies, simulations, and in-depth research, we will explore potential solutions and strategies to address these challenges. By understanding and discussing these critical areas, we aim to pave the way for the advancement and successful integration of AVs in tunnel environments.

3 Challenges and Solutions

This chapter centers on the operation of autonomous vehicles (AVs) in road tunnels, highlighting the safety factors associated with their deployment specifically in tunnels. The distinctive characteristics of road tunnels pose additional challenges that must be carefully addressed to ensure the safe and efficient operation of AVs. Among these challenges, human behaviors and technological advancements emerge as crucial factors that cannot be overlooked, particularly in road tunnels. To address these challenges, extensive research and investigation are essential to develop comprehensive solutions and mitigate potential risks. A detailed literature study is conducted to examine these aspects and shed light on the specific factors pertaining to AVs in road tunnels.

This study aims to provide a direction for future investigations in order to bridge the existing gaps and contribute to a more comprehensive understanding of the challenges associated with AVs. By addressing these challenges and conducting further research, it is possible to advance the knowledge and facilitate the development of effective solutions for the safe and efficient implementation of AVs.

In the next section, the Bayesian belief networks technique is discussed which is a powerful tool useful for visualizing complex systems and can help to structure discussions among stakeholders. They can also be used to simulate various scenarios and to perform sensitivity analyses, which help to identify which variables have the most impact on the overall risk.

3.1 Bayesian Belief Networks (BBNs)

According to SRA [2] risk is defined as "the consequences of the activity with associated uncertainties," in which it shows (C, U) where C represents the consequences of the activity and U signifies that these consequences are with uncertainties (Aven et al., 2018).

The consequences can be further divided into risk sources (RS), events (A), and consequences (C), which combined make up the definition of risk as outlined by Aven (2014), i.e. (RS, A, C, and U) along with the corresponding risk description (RS , A , C ,

[2]The Society for Risk Analysis (SRA) promotes understanding and effective management of risks through interdisciplinary collaboration, research, education, and outreach. It serves as a platform for exchanging knowledge, ideas, and best practices in risk analysis, assessment, communication, and management.

Q, and K). RS', A', and C' represent specific risk sources from where that risk is initiated, events that are going to be generated because of those risks, and consequences of those events in Autonomous vehicle activities, respectively. Q is a measure of uncertainty and K represents the background knowledge that supports RS', A', C', and Q.

Here Q is measured by (P, SoK, and K) where P is the qualitative probability which is the degree of belief in the outcomes of the events, SoK is the strength of knowledge that Q possessed and K is the knowledge. Here probabilities can be evaluated as high, moderate, or low which is connected with the strength of knowledge (SoK) if the strength of knowledge is strong, moderate, or weak (Andersen et al., 2022). Balancing the level of detail to promote understanding while avoiding excessive complexity is crucial in this process. The graphical structures illustrate causal relationships (risk sources, events, and consequences) and uncertainties in terms of subjective probabilities and strength of knowledge as shown in Figure 1. BBNs are based on Bayesian statistics and graph theory and use probabilistic models to represent uncertainty and causal relationships.

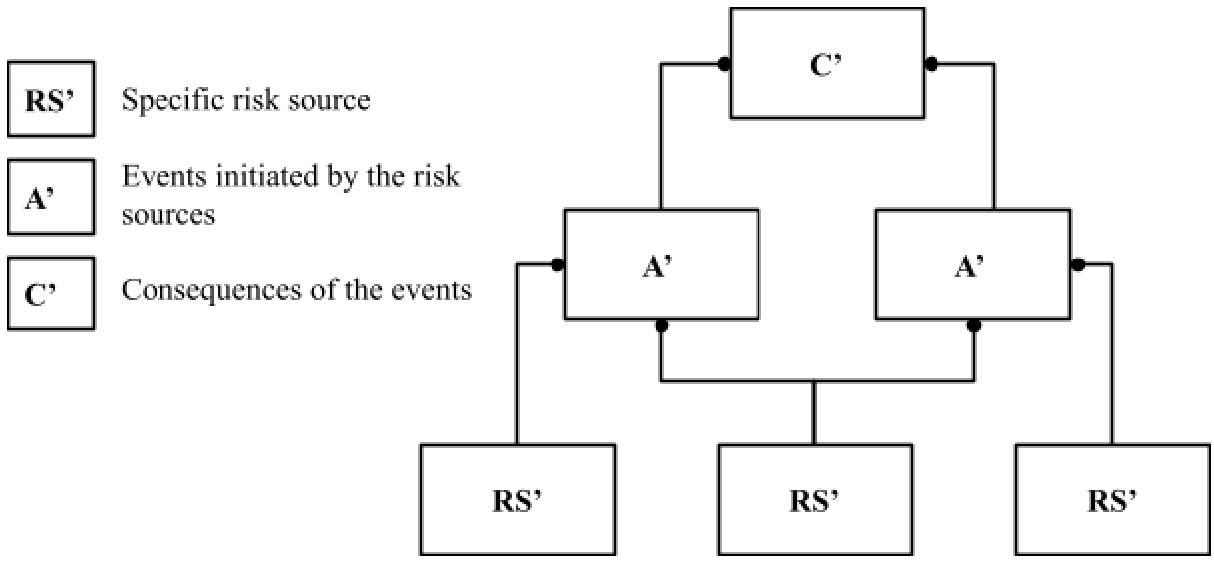


Figure 3.1: Basic BBNs Risk Picture

The Bayesian belief networks (BBNs) framework is employed in this study to establish a connection and analyze the inter-dependencies among the identified challenges in the context of AVs. BBNs provide a powerful tool for representing and quantifying uncertainties and dependencies in complex systems.

By utilizing BBNs, this research aims to showcase how the various challenges in AVs are interconnected and how they can collectively impact the overall risk associated with autonomous vehicle operations. The BBN approach allows for comprehensive visualization of the relationships and dependencies among these challenges, providing a holistic understanding of their combined effects (Bouckaert, 1995) (Steijn et al., 2020).

Furthermore, the use of BBNs enables the identification of critical factors and potential causal relationships that contribute to the uncertainties and consequences associated with AVs. This analysis aids in prioritizing research efforts and directing attention to areas that require further investigation and mitigation strategies.

Through the integration of BBNs, this study provides a systematic framework to examine the challenges of AVs and their interconnected nature, thereby enhancing the understanding of the risks involved. This approach offers valuable insights for policymakers, researchers, and practitioners, assisting them in making well-informed decisions and addressing the complexities associated with the execution of AVs in real-world scenarios (Jensen and Nielsen, 2007) (Sheehan et al., 2019).

3.2 Complete Risk Picture of the Challenges

The risk picture presented below in Figure 3.2 is a comprehensive analysis of the risks associated with AVs operating in road tunnels. By utilizing the Bayesian belief networks approach, the interconnections between the identified challenges related to AVs in road tunnels are illustrated. The significance of addressing these challenges and finding effective solutions is emphasized, highlighting their collective impact on risk. This chapter provides an overview of how risks are inherent in AVs in tunnels, as they can trigger events that lead to uncertain consequences. The subsequent section delves into a detailed discussion of each challenge, exploring their individual implications, suggested solutions, and their impact on the overall operation of AVs in tunnels, including the uncertainties they can introduce (Bezemskij et al., 2017).

This chapter underscores the importance of addressing the identified challenges and finding viable solutions. Recognizing that these challenges have direct implications for the safe and efficient operation of AVs in tunnels, it emphasizes the urgency of proactive measures. By thoroughly examining each challenge and its specific characteristics, this study aims to foster a deeper understanding of the underlying issues and drive the development of effective strategies to overcome them. The overall risk picture demonstrates how risks associated with AVs in tunnels can initiate events that lead to uncertain consequences. By exploring the interconnected challenges, this analysis highlights the potential cascading effects and the need for comprehensive risk management. It emphasizes the importance of proactive measures to mitigate risks, anticipates potential events, and ensure the overall safety and reliability of AVs in tunnel environments.

In addition to the overall risk picture, risk pictures of all the challenges are individually presented below as well in the next sections.

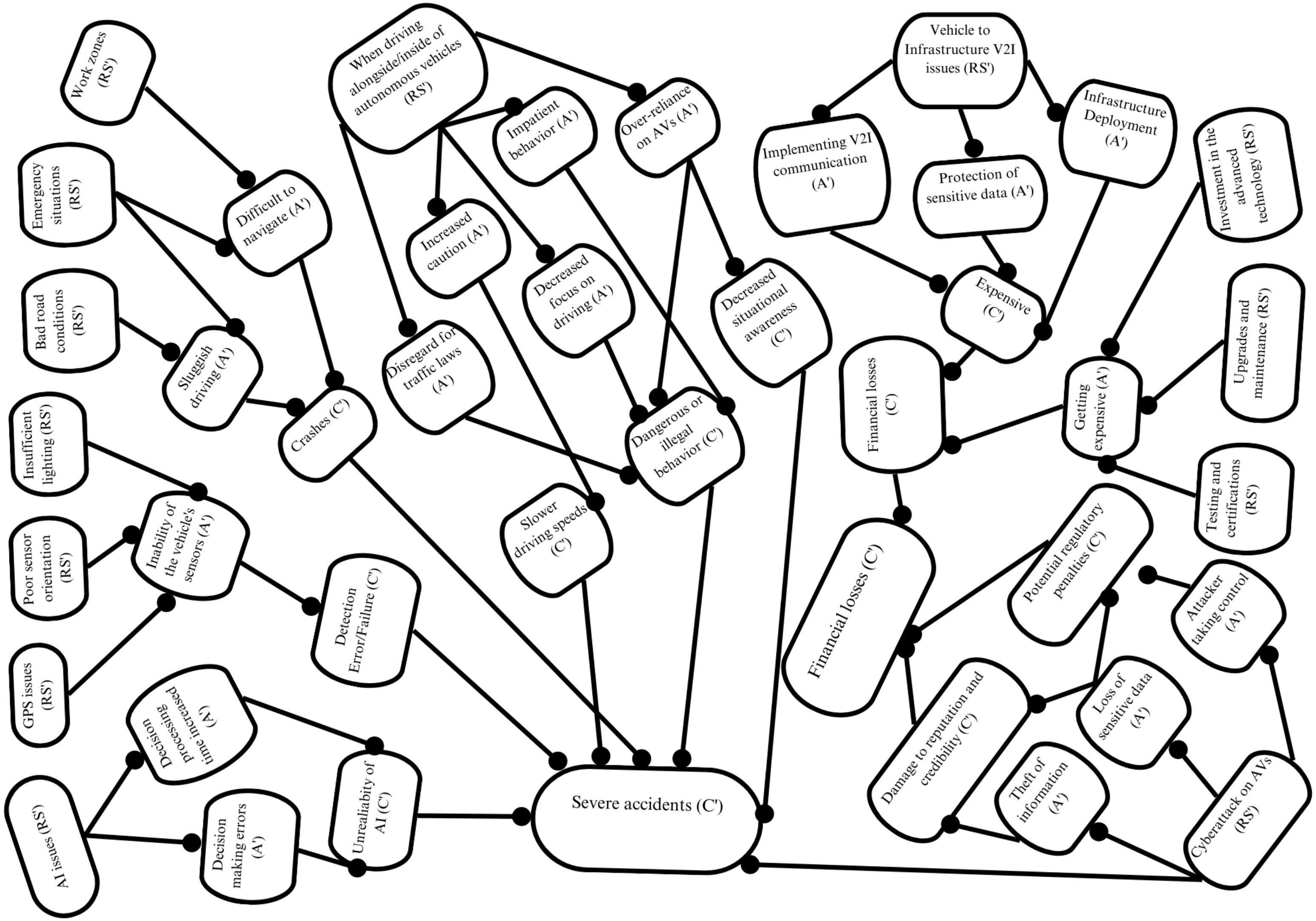


Figure 3.2: Complete Risk Picture in BBNs framework

3.3 Identified Challenges/Problems/Risk Sources

There are many challenges for AVs when they come in contact with the open road but there are many other uncertain problems as well that have been observed when AVs have to operate in the road tunnels. These challenges have been discussed thoroughly and some suggested solutions have been presented as follows.

The paper follows a structured scheme where challenges and their corresponding solutions are discussed in a sequential manner. Each challenge is explored in detail, followed by the presentation of its respective solutions. This systematic approach ensures that the reader gains a comprehensive understanding of each challenge before moving on to the next one and its associated solutions. By organizing the discussion in this manner, the paper offers a clear and logical progression, allowing for a more coherent exploration of the challenges and their potential resolutions.

However, it should be noted that these solutions come with certain limitations, and further research is necessary to address these issues effectively. While the studies mentioned below, present and propose solutions to various challenges. They do not delve extensively into these challenges, as it goes beyond the scope of this particular study. It is important to highlight that the study extensively examines the challenge associated with human behavior in road tunnels when it comes to AVs, providing a comprehensive analysis of this particular issue.

3.3.1 In-feasibility of Complete Training of AI algorithms

The feasibility of artificial intelligence (AI) in AVs for road tunnels has been widely explored and researched in recent years. The results have been promising as AI plays a crucial role in enabling AVs to navigate through tunnels safely and efficiently. AI algorithms such as computer vision, machine learning, and deep learning, help AVs to recognize and respond to various road conditions and scenarios, including obstacles, other vehicles, and road signs (Rao and Frtunikj, 2018).

However, there are still several technical and safety challenges that must be addressed before the widespread deployment of AI in AVs for road tunnels. One significant challenge is the in-feasibility of AI regarding its machine learning scalable training. Training AI algorithms require large amounts of data, which is difficult to acquire for specific scenarios that may occur within tunnels. Therefore, more research is needed to ensure that AI algorithms can be effectively trained for tunnel-specific scenarios (Zhou et al., 2020).

Another challenge is ensuring the reliability of AI algorithms used in AVs for road tunnels. The algorithms must be robust and reliable in handling unexpected situations, such as system failures, sensor malfunctions, or cyberattacks, to ensure safe operation in tunnels. Additionally, the testing and validation of AI in AVs must be conducted rigorously to ensure their safety and effectiveness in all driving conditions (Rao and Frtunikj, 2018) (Howard et al., 2017).

The subsequent BBNs risk picture highlights the significant repercussions that can arise due to the impracticality of fully training AI algorithms. Within the subsequent paragraph, potential solutions for addressing this issue are explored and presented.

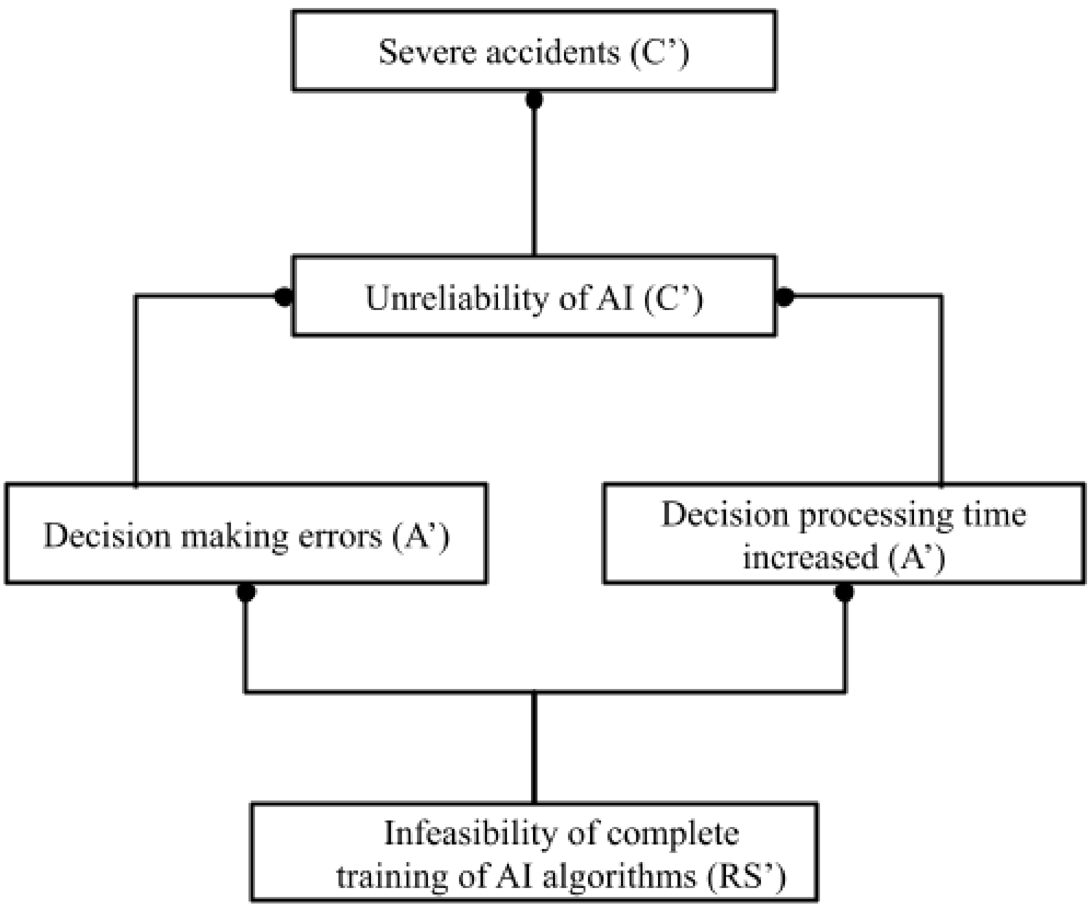


Figure 3.3: Risk Picture of In-feasibility of Complete Training of AI Algorithms

Suggested Solutions for AI Scalable Training:

The solution to this problem has been suggested by many experts and few of these are discussed here. Infeasibility of complete training of AI algorithms is a challenge and it needs scalable training, different solutions have been proposed and these are the following:

Collaborative Training

Collaborative training in which connected vehicles generate large amounts of data that can be used to improve the performance of autonomous driving systems. However, due to limited communication bandwidth and privacy concerns, it is often not feasible to transmit all the data to a central server for processing.

The proposed framework by Lu et al. (2019) uses collaborative learning to train machine learning models on the edge devices themselves, allowing the models to learn from the data generated by each vehicle without the need for centralized data storage or processing. The authors demonstrate the effectiveness of this approach through experiments on a large-scale connected vehicle dataset. The results show that the collaborative learning approach can significantly improve the performance of machine learning models for connected vehicles and AVs, while also reducing the communication overhead and preserving data privacy. This framework has been discussed by Zhao et al. (2021) and Ghimire and Rawat (2022) in their studies as well.

Model Compression Technologies

Model compression technologies introduce a method for training deep neural networks with binary weights. Binary weights refer to weights that can only take on two values, typically +1 or -1, instead of the continuous values used in traditional neural networks. Binary weights reduce the storage and computational requirements of the network, making it faster and more energy-efficient (Roy et al., 2019).

The proposed method by Courbariaux et al. (2016) trains the network with binary weights by introducing a stochastic binarization step during the forward propagation of the network, which allows the weights to be binary but still update during backpropagation. In similar studies, authors show that this approach can achieve similar accuracy to traditional neural networks while using significantly fewer resources (Roy et al., 2019).

Lightweight Machine Learning Algorithms

This method is proposed by Howard et al. (2017) and introduces a family of efficient convolutional neural networks (CNNs) designed for mobile and embedded vision applications. Mobile vision applications typically have limited computational resources, making it difficult to use traditional deep neural networks that require large amounts of computation and memory. Mobile-Nets address this problem by using depth-wise separable convolutions, which separate the spatial and channel-wise filtering operations. This allows for more efficient computation and a reduction in the number of parameters needed for the network. The authors present several variants of Mobile-Nets with different levels of computational complexity and accuracy trade-offs. They show that Mobile-Nets can achieve state-of-the-art accuracy on various vision tasks while being much more efficient than traditional CNNs.

Mobile-Nets have been widely adopted and have been used in many mobile vision applications, such as image recognition, object detection, and semantic segmentation in AVs (Minaee et al., 2021). These solutions can be an answer to the in-feasibility of complete training of AI algorithms in AVs but these solutions have some constraints and more research is required for this purpose.

3.3.2 Bad Road Conditions/ Emergency Cases/ Work Zones

Bad road conditions, emergency situations, and work zones all pose substantial challenges for AVs in road tunnels (Zang et al., 2019). This might result in abrupt stops, sluggish driving, or even crashes. Tackling this kind of condition even with the help of machine learning and testing methods is not effective (Hnewa and Radha, 2021). Road closures, accidents, and other unforeseen incidents can potentially offer substantial hurdles for AVs. To protect the safety of passengers and other road users, cars must be able to respond rapidly and make judgments based on real-time information.

Work zones, such as building sites or road maintenance regions, can also be difficult for AVs to navigate. These zones are constantly changing, with vehicles and equipment moving about, making it challenging for the AV to comprehend and respond to its surroundings appropriately as shown in the risk figure below (Tang et al., 2021).

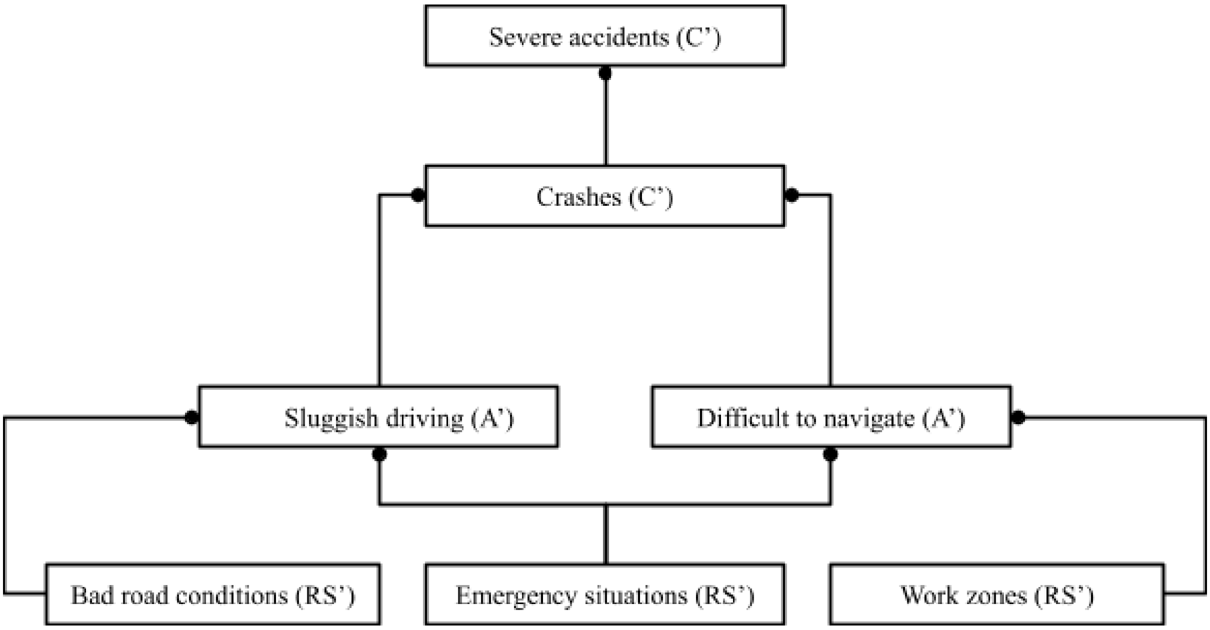


Figure 3.4: Risk picture of Work Zones/ Bad Road Conditions

Solutions for Work Zones/ Bad Road Conditions:

Recognizing work zones is one of the challenges for AVs to detect, to tackle this kind of problem a solution is proposed by Seo et al. (2014) where they present a method for AVs to recognize highway work zones, which can be challenging due to their dynamic nature. The proposed method uses a combination of sensors such as cameras and LiDAR to detect and classify different types of work zones, including lane closures, construction areas, and maintenance zones. The method also incorporates machine learning algorithms to improve the accuracy and reliability of the work zone detection.

Once a work zone is detected, the method provides instructions to the autonomous vehicle to adjust its behavior accordingly. For example, the vehicle may be instructed to reduce speed, change lanes, or follow a different path to avoid the work zone. The authors Liu et al. (2021) claim that the proposed method is reliable and effective in recognizing different types of work zones and providing adequate instructions to the autonomous vehicle. They provide experimental results to demonstrate the effectiveness of the method.

Bad road conditions can cause many uncertain consequences and to deal with this kind of problem a solution is presented by (Hilgert et al., 2003) but contradicted by Kaempchen et al. (2009). The focus of this method is an approach to path planning for AVs in emergency situations, where the vehicle needs to quickly avoid obstacles and change its path to reach a safe location.

The method is based on the concept of elastic bands, which are virtual bands that are stretched between the vehicle and the obstacle. The goal is to find a path that follows the elastic bands and avoids collisions with obstacles. The method also takes into account the dynamic constraints of the vehicle, such as its speed and turning radius.

To implement this method, the vehicle's environment is first scanned to identify any obstacles. The elastic bands are then generated between the vehicle and the obstacles, and a path is planned that follows the elastic bands while taking into account the vehicle's dynamic constraints. The method also includes a feedback loop to adjust the path if new obstacles are detected or if the vehicle's state changes. Overall, this method provides a way for AVs to quickly and safely navigate emergency situations, such as avoiding collisions with other vehicles or pedestrians, by using elastic bands and taking into account the vehicle's dynamic constraints.

To avoid obstacles in emergency situations a method is proposed by Guo et al. (2016) for AVs using vision-based sensing and control. The method uses cameras or other vision-based sensors to detect obstacles and estimate the vehicle's position and velocity. A nonlinear control system is then used to coordinate the steering and braking of the vehicle to avoid obstacles while maintaining vehicle stability. The approach considers the vehicle's motion dynamics and the interaction between the steering and braking systems to achieve optimal control. The proposed method is designed to handle a wide range of emergency scenarios and obstacles, including sudden stops, pedestrians, and other vehicles. Liang et al. (2020) claim that the proposed method achieves better obstacle avoidance performance compared to other control methods for AVs in emergency scenarios. Although given the extent of limited knowledge about this topic, further research is important in order to gain a more comprehensive understanding.

3.3.3 Cyberattack on AVs

A cyberattack on AVs in road tunnels can have far-reaching consequences, including disruptions in the normal functioning of vehicles, loss of sensitive data, financial losses, damage to reputation and credibility, and potential regulatory penalties and legal consequences. One of the primary concerns with AVs is their vulnerability to hacking. The complex network of sensors, cameras, and control systems that make up an autonomous vehicle's driving system can provide a tempting target for cybercriminals. A successful cyberattack on an autonomous vehicle in tunnels could result in the attacker taking control of the vehicle and causing it to crash, or disrupting the normal functioning of the vehicle in ways that could lead to accidents. In addition, AVs are often equipped with sophisticated systems that collect and store vast amounts of sensitive data, including personal information, driving patterns, and location data as shown in Figure 3.5 A cyberattack on such a system could result in the theft of this information, which could be used for malicious purposes such as identity theft or targeted advertising (Malik and Sun, 2020).

Another concern with AVs is their potential to cause widespread disruption if they are targeted by a cyberattack. For example, an attack that takes down a fleet of AVs could result in widespread transportation disruptions in the tunnels, which could have serious consequences for businesses and individuals alike. In addition, AVs are often connected to other systems of the tunnels, such as traffic control systems and cloud-based data centers. A successful cyberattack on these systems could have far-reaching consequences, including widespread power outages and other infrastructure disruptions (Komkov and Petiushko, 2021). To handle these kinds of issues in the following paragraphs solutions to these challenges are proposed.

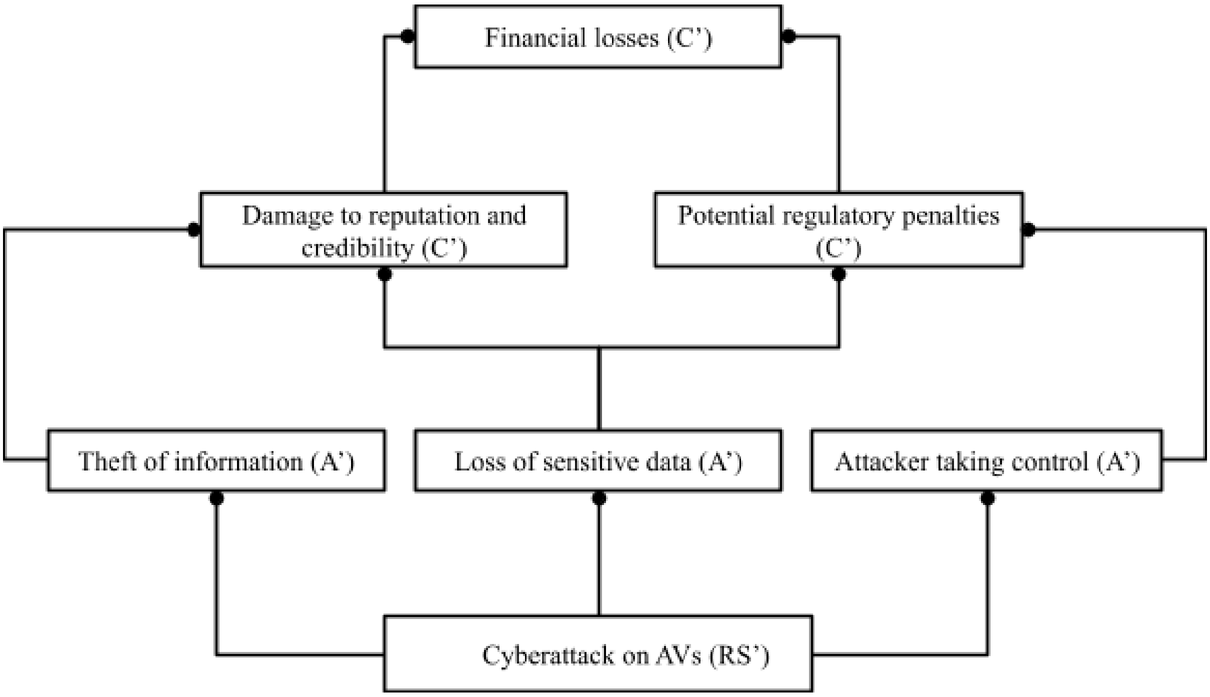


Figure 3.5: Risk Picture of Cyberattacks

Solutions for Cyberattacks

Bernstein and Lange (2017) proposed a solution in which it discusses a cryptographic approach that aims to resist attacks by quantum computers. Quantum computers have the potential to solve certain problems much faster than classical computers, which could pose a threat to current cryptographic systems. The authors propose a "post-quantum cryptography" approach that involves developing new cryptographic algorithms that are resistant to attacks by quantum computers. This approach provides an overview of different cryptographic primitives such as encryption, signature schemes, key exchange and the challenges of developing post-quantum cryptography for each of these primitives are discussed. The authors also present some post-quantum cryptographic algorithms that have been developed, such as lattice-based cryptography, code-based cryptography, and hash-based cryptography. Hassija et al. (2020) argue that it is important to start developing and implementing post-quantum cryptography now, as quantum computers are expected to become more powerful in the future, and the transition to post-quantum cryptography will take time.

Overall, Bernstein and Lange (2017) addresses the importance of developing new cryptographic algorithms that can resist attacks by quantum computers and presents some post-quantum cryptographic algorithms that have been developed. Another solution proposed by Ning et al. (2017) talks about the challenges associated with securing hardware-assisted execution environments. Hardware-assisted execution environments, such as Intel SGX, provide a secure environment for executing code and protecting sensitive data. However, these environments are not immune to attacks and can be compromised if not properly secured. Ning et al. (2017) identifies several challenges associated with securing hardware-assisted execution environments, including the lack of visibility into the execution of code within these environments, the risk of side-channel attacks, and the need for secure communication between different components of the system. The authors propose several solutions to address these challenges, such as using hardware-based attestation to verify the integrity of code and data within the environment, implementing secure channels for communication, and utilizing software-based countermeasures to mitigate the risk of side-channel attacks.

Overall, the paper highlights the importance of securing hardware-assisted execution environments and proposes solutions to address the challenges associated with this task.

To mitigate these risks, robust cybersecurity measures must be implemented throughout the design, development, and deployment of AVs. This includes secure communication protocols, strong encryption mechanisms, intrusion detection systems, regular software updates, and rigorous penetration testing. Additionally, the collaboration between automotive manufacturers, infrastructure operators, and cybersecurity experts is crucial to address vulnerabilities and establish comprehensive security frameworks (Zhang et al., 2018).

3.3.4 Detection and Sensors Inability

There are several risk sources when it comes to sensors' inability such as GPS signals can be blocked or degraded in road tunnels, making it difficult for AVs to accurately determine their location and navigate through the tunnel. This can increase the risk of collisions and other safety issues (Braid et al., 2006).

Limited Visibility

Tunnels can have limited lighting, making it difficult for AVs to detect obstacles or other vehicles. This can increase the risk of collisions, especially if the vehicle's sensors are not able to detect objects in the dark (Arnold et al., 2019).

Detection Failure

Detection failure in AVs refers to the inability of the vehicle's sensors (cameras, LiDAR, radar, or ultrasonic sensors) to accurately detect and identify objects in the driving environment. This can lead to incorrect decisions made by the vehicle's AI system, resulting in collisions, near-misses, or other safety incidents. Some common causes of detection failure include poor sensor placement/orientation, insufficient lighting, obscured objects and high levels of ambient noise. It's important for AV developers to address these challenges and ensure that their systems are equipped with steady and reliable detection capabilities to enhance safety and improved performance (Yan et al., 2016)(Tang et al., 2020). Undoubtedly, these issues can lead to uncertain consequences which can be chaotic in the congested environment of the tunnel as shown in the appended Figure 3.6 as well.

Although immediate attention to this topic is required but this study primarily focuses on the safety of AVs with vehicle-to-human interaction rather than the technical capabilities of sensors which fall outside the scope of this research which is why solutions to these issues are not discussed here.

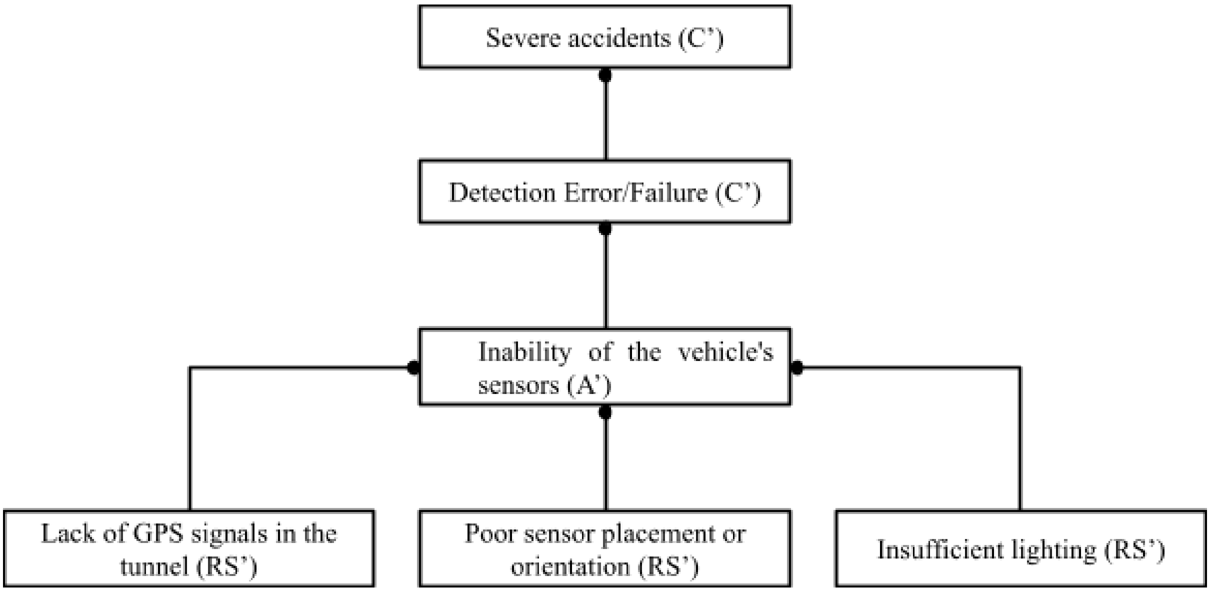


Figure 3.6: Risk Illustration of Sensors Inability

3.3.5 Vehicle-to-Infrastructure V2I Issues

Vehicle-to-infrastructure (V2I) communication is a crucial component of autonomous vehicle technology, as it enables vehicles to communicate with the infrastructure and other road users to enhance safety and improve the overall driving experience. (Bowers et al., 2016) However, there are several challenges associated with V2I communication in AVs, including:

Interoperability: V2I communication requires standardized protocols and technologies to ensure that vehicles and infrastructure can communicate effectively. This can be a challenge, as different manufacturers may use different protocols and technologies, resulting in a lack of interoperability as shown in Figure 3.7.

Infrastructure Deployment: Deploying the infrastructure needed for V2I communication is a complex and costly process and thus requires significant investment. This includes the installation of sensors, cameras, and other equipment, as well as the development of new software /systems.

Security: V2I communication requires secure communication channels to prevent unauthorized access and protect sensitive data. This is a challenge, as cyber criminals may attempt to intercept or disrupt V2I communication to gain unauthorized access to vehicles or other systems.

Latency: V2I communication must be fast and reliable to ensure that vehicles receive critical information in real-time. As the communication infrastructure may experience latency due to a variety of factors, such as congestion or poor signal quality that can cause hiccups.

Cost: Implementing V2I communication can be expensive, as it requires the deployment of new infrastructure and technologies. This should be cost-efficient ensuring that the benefits of V2I communication are accessible to all road user types (individuals and organizations) (Tengilimoglu et al., 2023b).

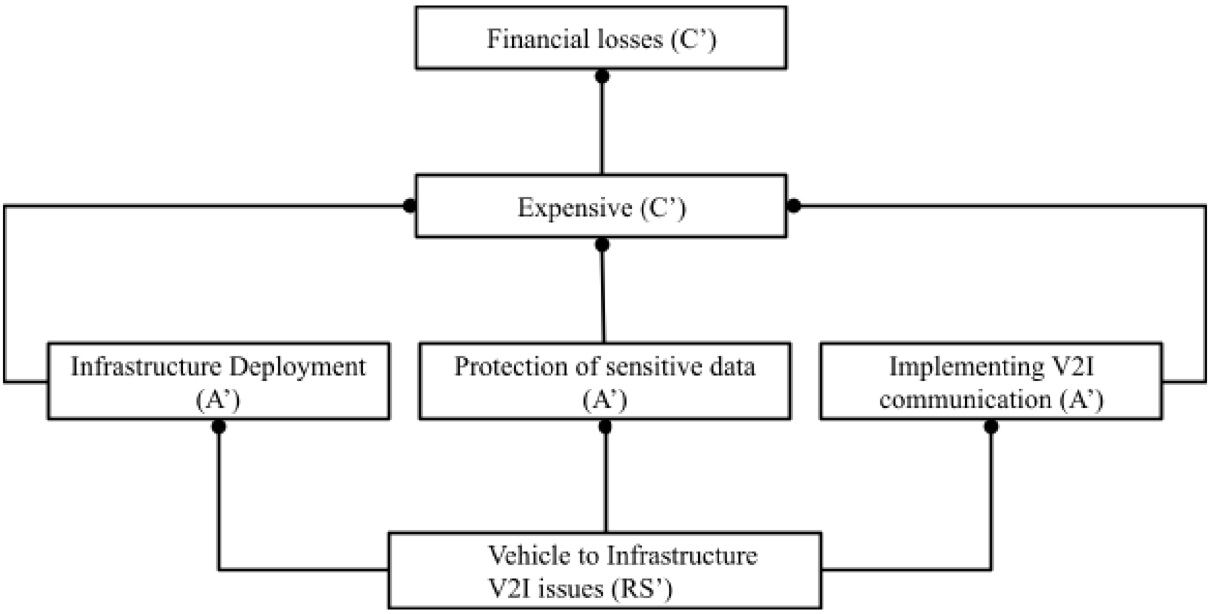


Figure 3.7: Risk Picture of V2X Issues

3.3.6 Cost Issues

The development and deployment of AVs in road tunnels can be a costly process, involving significant investments in research and development, testing, and manufacturing. Some of the cost issues described in (Litman, 2017) associated with AVs in tunnels include:

Research and Development: Advance technologies require consistent investments and development in software systems that can operate effectively in the tunnel environment which is a costly process in terms of research and development.

Testing and Certification: AVs operating in tunnels must undergo extensive testing and certification before they can be deployed. This process can be time-consuming and expensive, requiring specialized equipment and highly skilled personnel to ensure the vehicles can operate safely and efficiently within the tunnel environment.

Manufacturing: The manufacture of AVs for tunnel environments requires specialized components and systems that can be more expensive than traditional components used in conventional vehicles. Companies must also ensure that the vehicles are designed and manufactured to meet the unique challenges of tunnel driving (Tengilimoglu et al., 2023b).

Liability: It is unclear who will be responsible if an autonomous vehicle is involved in an accident within the tunnel environment. This uncertainty can increase the cost of insurance for AVs, making them more expensive and less affordable for consumers as shown in Figure 3.8

Infrastructure: The AVs need special infrastructure, such as sensors, communication systems and traffic control systems. Building and maintaining this infrastructure causes an increase in CAPEX and OPEX (Seo and Asakura, 2022).

Upgrades and Maintenance: AVs operating in tunnels require frequent software updates and maintenance to keep their systems functioning correctly and to stay up to date with the latest advancements in technology. These upgrades and maintenance costs can add up over time, making AVs more expensive to operate in the long run (LeVine, 2017).

It's important to note that while the initial costs of autonomous vehicle infrastructure can be high, there can also be long-term benefits, such as improved traffic flow, enhanced safety, and reduced environmental impact. Additionally, cost efficiencies may arise as the technology matures and for that purpose, further research is required with some analyses such as cost-effective or cost-benefit analysis (Litman, 2017).

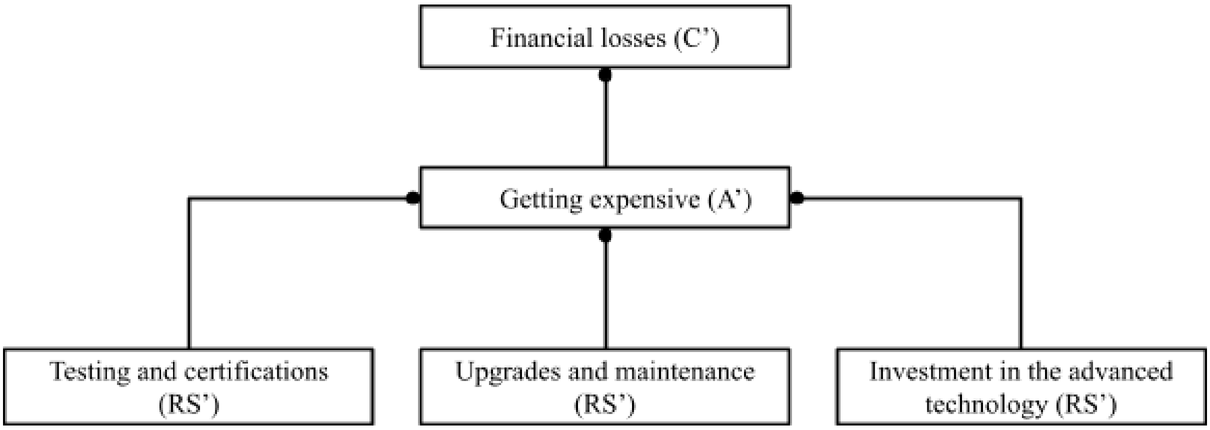


Figure 3.8: Risk Picture of Cost issues

3.3.7 Human Unpredictable Behavior

Drivers may behave differently when driving alongside AVs in road tunnels (Soni et al., 2022)(Schoettle, 2017). Some behavioral changes are:

Increased Caution: Drivers may exhibit increased caution when driving alongside AVs, due to a lack of familiarity with the technology and its capabilities. This may result in slower speeds and greater following distances between vehicles in the tunnel.

Over-Reliance on AVs: Some drivers may become overly reliant on AVs, assuming that the technology will always operate correctly and make safe decisions. This can lead to decreased situational alertness and a higher risk of accidents if the technology fails or encounters an unexpected situation.

Impatient Behavior: Some drivers may become impatient when driving alongside AVs, especially if they are traveling slower or have trouble merging or changing lanes. This can result in dangerous maneuvers, such as tailgating or sudden lane changes.

Disregard for Traffic Laws: Some drivers may disregard traffic laws while driving along AVs, assuming that the technology will always follow the rules of the road tunnels. This can lead to dangerous or illegal behavior.

Decreased Focus on Driving: Some drivers may become less focused while driving when driving alongside or inside of AVs, distracted by using their phones or eating. The illustration in Figure 3.9 shows uncertainties in human behavior.

The presented risk picture shows the potential for adverse outcomes arising from various risk sources while acknowledging the presence of uncertainties. This serves as a clear indication that immediate attention is required in this area, calling for further comprehensive studies to go deeper into these risks and devise effective mitigation strategies. The subsequent chapter provides a detailed analysis of this issue and proposes effective solutions to address these challenges.

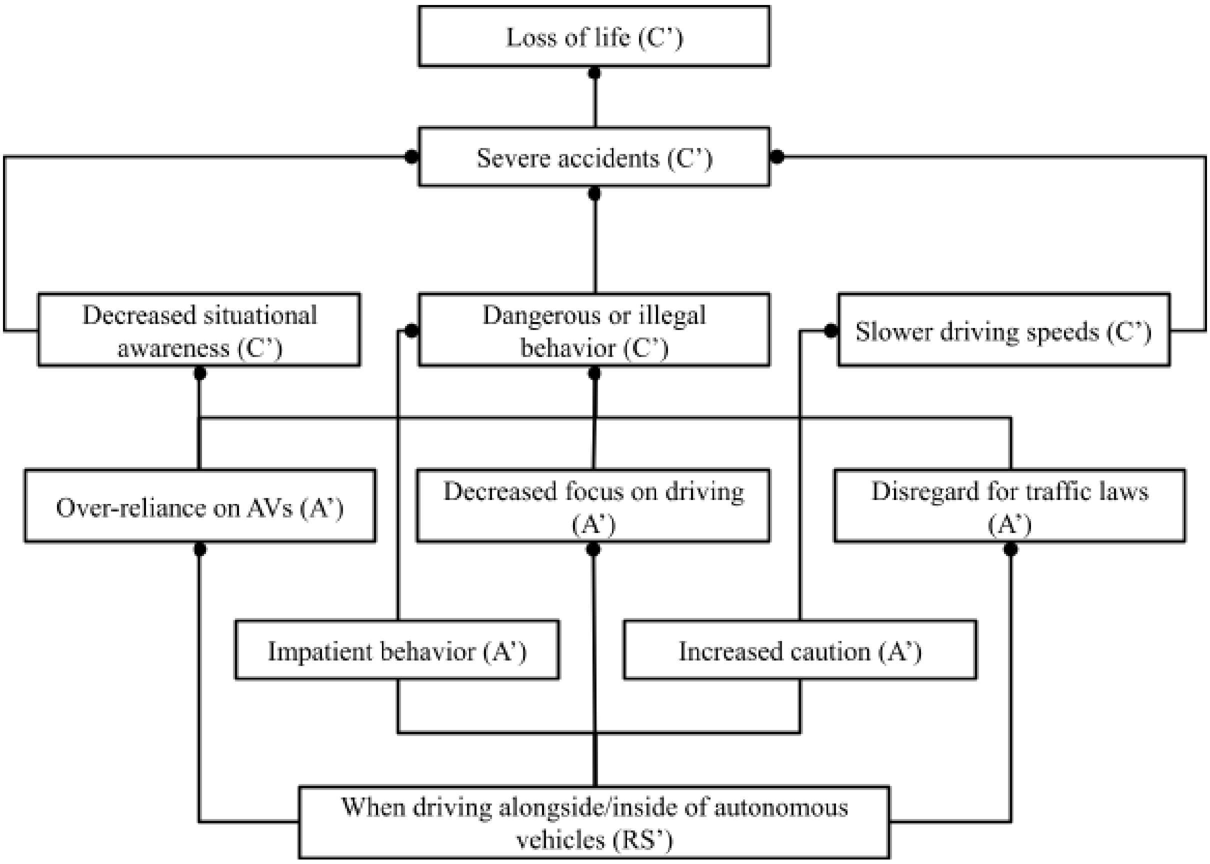


Figure 3.9: Risk Picture of Unpredictable Human Behavior in Road Tunnels along AVs

4 Human Behavioral Challenges

Human Behavior When Interacting with Autonomous Vehicles in Road Tunnels:

Road tunnels are unique structures that present a variety of challenges to drivers. They are enclosed, with low light and visibility, and have specific design features that can impact driver behavior. As a result, drivers may behave unpredictably in tunnels, potentially leading to accidents and other safety issues when driving along AVs.

4.1 Lighting Conditions

One of the most significant factors is the transition from daylight to artificial light inside tunnels. The sudden shift from bright natural to artificial light can pose challenges for AVs' perception systems, which rely on visual cues for navigation and object detection. Robust adjustment of sensors, cameras and perception algorithms is necessary to ensure optimal performance (Kim, 2020).

Besides, uneven or inconsistent lighting levels within tunnels can also impact AVs' perception capabilities. Shadows, reflections, or areas with inadequate light can hinder the accurate identification of objects, road markings or potential hazards. This can lead to issues such as miscalculating speed (distance) and difficulty in detecting obstacles or other vehicles. At the same time, drivers need to adapt in varying light intensities, which can be disorienting and that can lead to erratic behavior (Miller and Boyle, 2015). On the other hand, the bright light at the end of the tunnel can cause temporary blindness, making it difficult for drivers to see other vehicles, pedestrians, and obstacles creating unpredictable scenarios for AVs to process in the meantime (Maurer et al., 2016) (Fuest et al., 2020) (Bassan, 2016).

In the tunnels, different kinds of lights are required for lane positioning, if image-based lane recognition is used then a low level of light is an issue in road tunnels for AVs. In addition to that, vision-based systems can fail because of the rapid change of light at the exit and entrance of the tunnels (Tengilimoglu et al., 2023a).

4.1.1 Lightning Problems and Solutions

Flickering lights can have a significant impact on drivers in road tunnels, as they can cause discomfort, disorientation and accidents. This effect is commonly known as the *"Stroboscopic Effect"* (Peña-García, 2018).

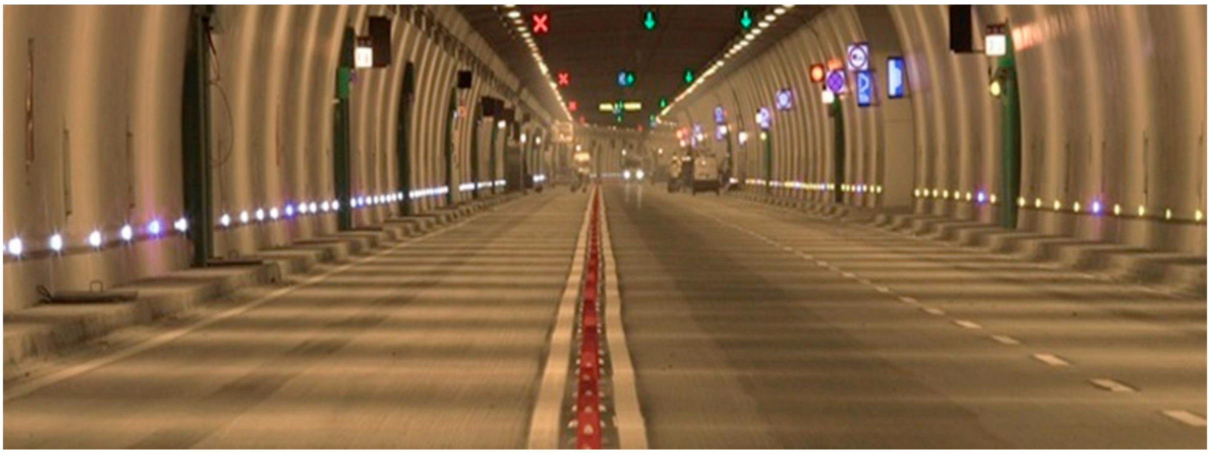


Figure 4.1: An Example of Flickering of Lights in Road Tunnels by (Peña-García, 2018)

The stroboscopic effect is a phenomenon where the rapid or freezing illusion of motion is created by the flashing of light. This can be distracting for drivers and can cause them to lose concentration, so it's important to eliminate this effect (Miller et al., 2023). Here are some ways to reduce the stroboscopic effect in road tunnels by (Moretti et al., 2017):

Increase the light intensities: Increasing the light levels in the tunnel can help reduce the contrast between light and dark areas, which is energy-consuming and expensive.

Use full-spectrum lighting: Full-spectrum lighting can help reduce the stroboscopic effect by providing a more natural light source.
Use LED lighting: LED lighting can help reduce the stroboscopic effect by providing a more uniform light source.
Use Diffusers: Diffusers can help reduce the stroboscopic effect by dispersing the light more evenly throughout the tunnel.
Reduce the spacing between light sources: Reducing the space between light sources can help reduce the stroboscopic effect by reducing the contrast between light and dark areas.

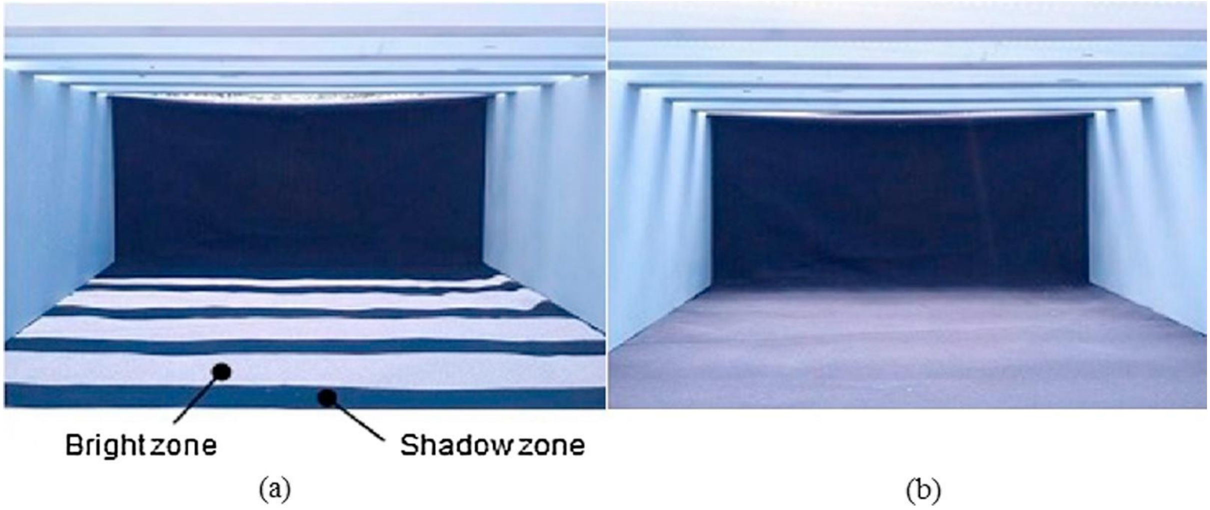


Figure 4.2: Solution to the Lightening Issues in RT's by (Peña-García, 2018)

It's worth mentioning that the design and layout of the tunnel can also impact the stroboscopic effect. If you're designing a new tunnel, consider using a design that minimizes the contrast between light and dark areas and provides a uniform light source (Peña-García, 2018).

4.1.2 Decorated Walls as Stress Relievers

Drivers have faced stress and distraction due to the monotonous driving in the road tunnel and that can be dangerous may result in road accidents (Thiffault and Bergeron, 2003). To avoid this there are multiple solutions given by experts and one of them is using visuals and decorated sidewalls in road tunnels. Studies show promising results to improve the environment of the road tunnels for drivers by using fMRI technology (Chen et al., 2020).

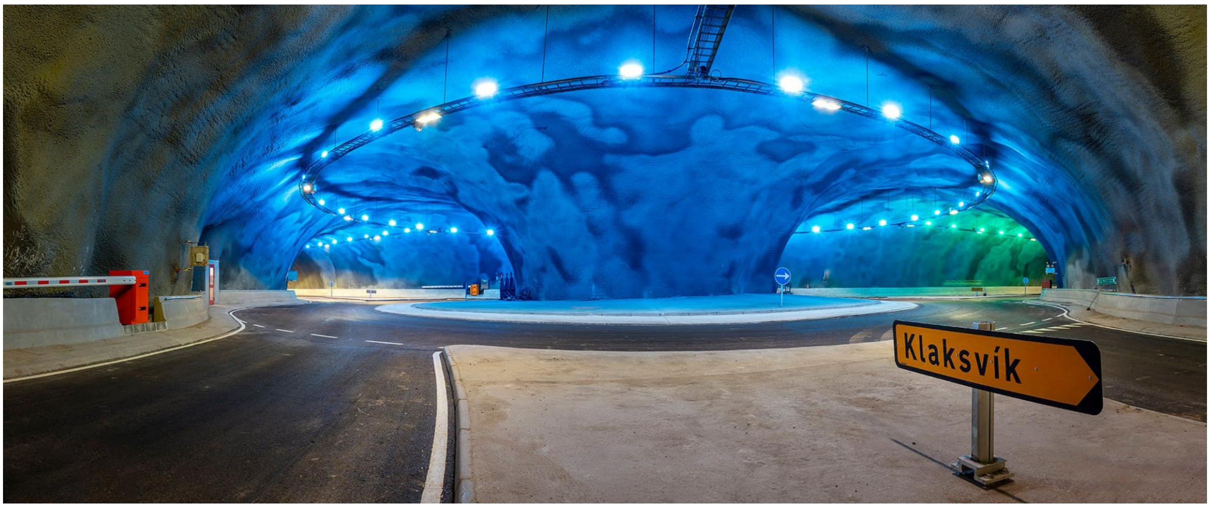


Figure 4.3: A Glimpse of a Decorated Road Tunnel by Ólavur Frederiksen

With this method, there will be better spatial and speed perception which can reduce accidents that are associated with speed judgments. Kircher and Ahlstrom (2012) also showed that light and tunnel design has some influence on the driver's behavior but visuals play an important role while driving through the tunnels.

To sum up, improving tunnel lighting and incorporating visuals can enhance visibility, driver safety and reduce accidents in road tunnels. Measures such as increasing light intensities, utilizing uniform and full-spectrum lighting and implementing decorative sidewalls; contribute to a better driving environment.

4.2 Design of the Tunnels

Another contributing factor is the design of the tunnels which can also impact the ability of AVs to navigate safely. Narrow lanes, sharp curves and steep gradients can be particular challenges for AVs, which are difficult to maintain a consistent speed or trajectory. Furthermore, tunnels can become congested, especially during peak traffic hours. This can cause drivers to become frustrated, impatient and aggressive, leading to erratic behavior that can impact the efficiency of AVs systems, leading to delays and decreased performance (Kircher and Ahlstrom, 2012). At the same time, tunnels also have a psychological impact on drivers, leading to unpredictable behavior. For some drivers, the enclosed space of the tunnel can cause feelings of claustrophobia or anxiety (Worm, 2006).

Surveys showed that drivers tried to adopt inappropriate behavior while driving through the tunnels for example not maintaining a safe distance, speeding and lane hopping (Lee et al., 2022). This can cause drivers to speed up, brake suddenly or attempt to exit the tunnel as quickly as possible. Studies showed that one of the main influencing factors is keeping a safe distance between the vehicles, the longer the distance between the vehicles in the tunnel the better it results in stressful situations (Arias et al., 2008). Suggestions are provided to change the behavior of the driver by showing color visuals, colorful decorations and the colorful environment of the tunnels that can provide driver comfort and safety. On the other hand, too much color information in the tunnel can result in a negative impact on the drivers (Qin et al., 2020).

4.3 Ethical Considerations

Moreover, there are also ethical considerations related to the behavior of AVs and their impact on human behavior. For example, if an AV is involved in an accident, how should it prioritize the safety of its passengers versus other road tunnel users? Should it always prioritize the safety of its passengers, or should it be programmed to prioritize the safety of other tunnel users in certain situations? (Maurer et al., 2016).

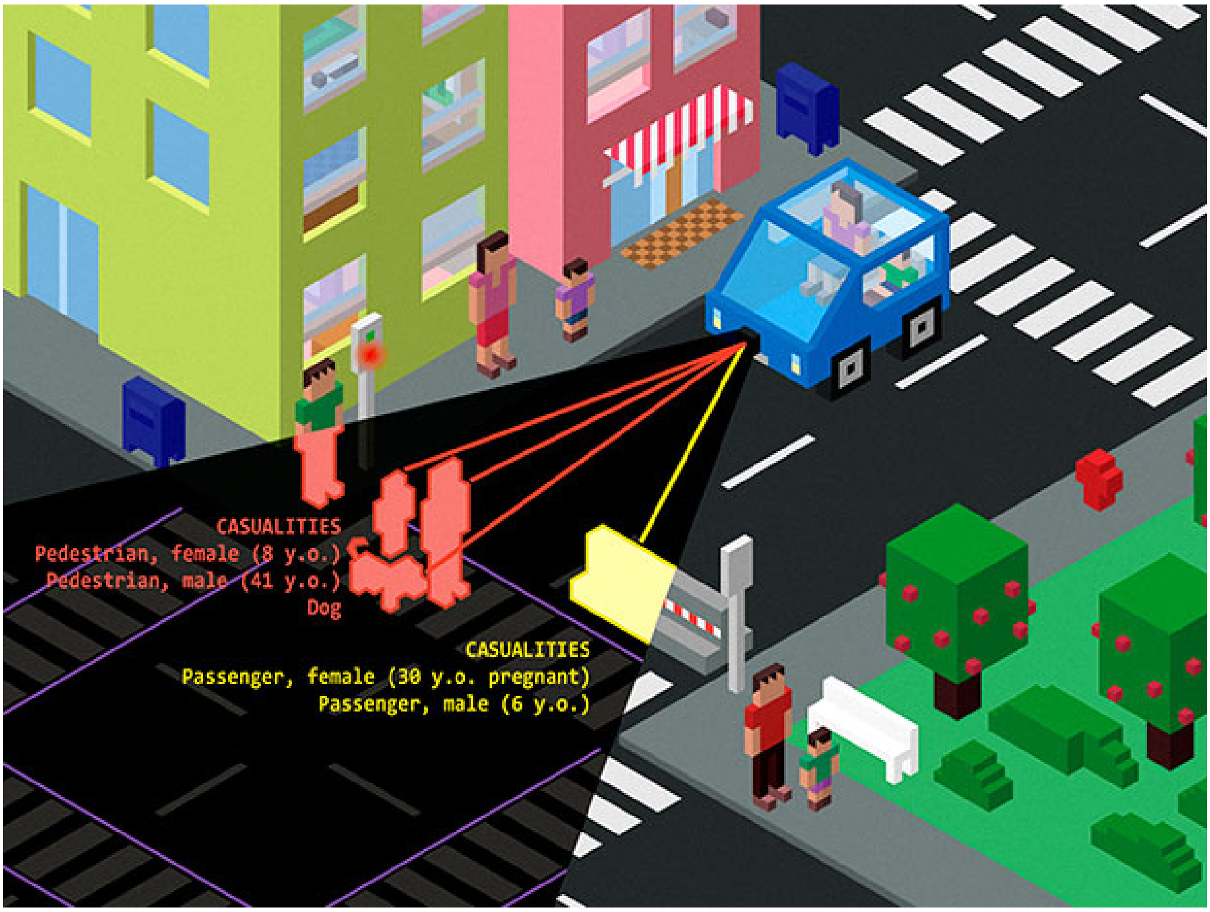


Figure 4.4: An Illustration of Ethical Consideration by Iyad Rahwan

These are difficult ethical questions that require careful consideration and debate. Ultimately, the behavior of AVs must be guided by a set of clear and transparent ethical principles that prioritize the safety and well-being of all road users, while also taking into account the practical limitations of the technology. Some of the optimizations are suggested as a solution if AVs have the priority to protect the occupants then AVs will eventually hit lighter-weight objects for example bikes or lightweight vehicles rather than hitting a truck but it is still against the codes of ethics (Wallach and Asaro, 2020). Optimization can be made in that way where any AVs have to choose the course of action where there is the least harm or injury to anyone. However, It is challenging to have codes of ethics that work for everyone. Either it is protection for someone on the other hand it can be considered selfishness for someone else (Maurer et al., 2016).

4.4 Risk Aptitude in Behavior

Another factor is that drivers are sometimes engaged in risky behavior when sharing the road with AVs, such as tailgating, cutting off, or intentionally blocking the AVs. These behaviors can create unsafe driving conditions not for AVs only but all road users. It can also lead to unnecessary wear and tear on the AVs' sensors and equipment (Soni et al., 2022). If drivers have negative attitudes towards AVs, they may be more likely to engage in risky behavior or resist sharing the road with AVs. Some drivers may be overconfident while driving alongside AVs, assuming that the technology is infallible and that they do not need to exercise the same caution they would with a driver. It is reckless driving behavior and a false sense of security.

In the same vein, there is a lack of trust in some drivers for AVs, either because of negative media coverage or because they have had a bad experience with the technology in the past. This lack of trust can lead to anxiety and erratic driving behavior when sharing the tunnel with AVs (Rödel et al., 2014) (Feldhütter et al., 2016).

Some drivers may intentionally act aggressively towards AVs, either out of a desire to prove their dominance on the road or out of frustration with the perceived slow speed or cautious behavior of the AVs. Conversely, if drivers have positive attitudes towards AVs, they may be more willing to follow safety guidelines and engage in cooperative behavior in the tunnel.

4.5 Communication Hiccups

Another potential issue is the lack of communication between human drivers and AVs. Drivers rely on nonverbal cues, such as eye contact and hand gestures, to communicate with other drivers on the roads and in some manners in the tunnels. In addition to that, there is always cultural difference as well. For example, in different countries, different gestures have been used in traffic (Broszinsky-Schwabe, 2017).

Figure 4.5: Basic Hand Signals for Driving provided by philkotse.com

AVs, on the other hand, rely on more technical means of communication, such as flashing lights and sensors. This lack of clear communication can lead to misunderstandings and misinterpretations, which can ultimately compromise safety on the road. For example, drivers may not understand the intentions of AVs, or may not realize that the AVs are following different rules of the road (Stanciu et al., 2018) (Chen et al., 2015).

However, AVs do not have the ability to interpret or respond to these non-verbal cues in the same way that drivers do. Here are some more examples of how the lack of non-verbal communication could affect the interaction between AVs and drivers:

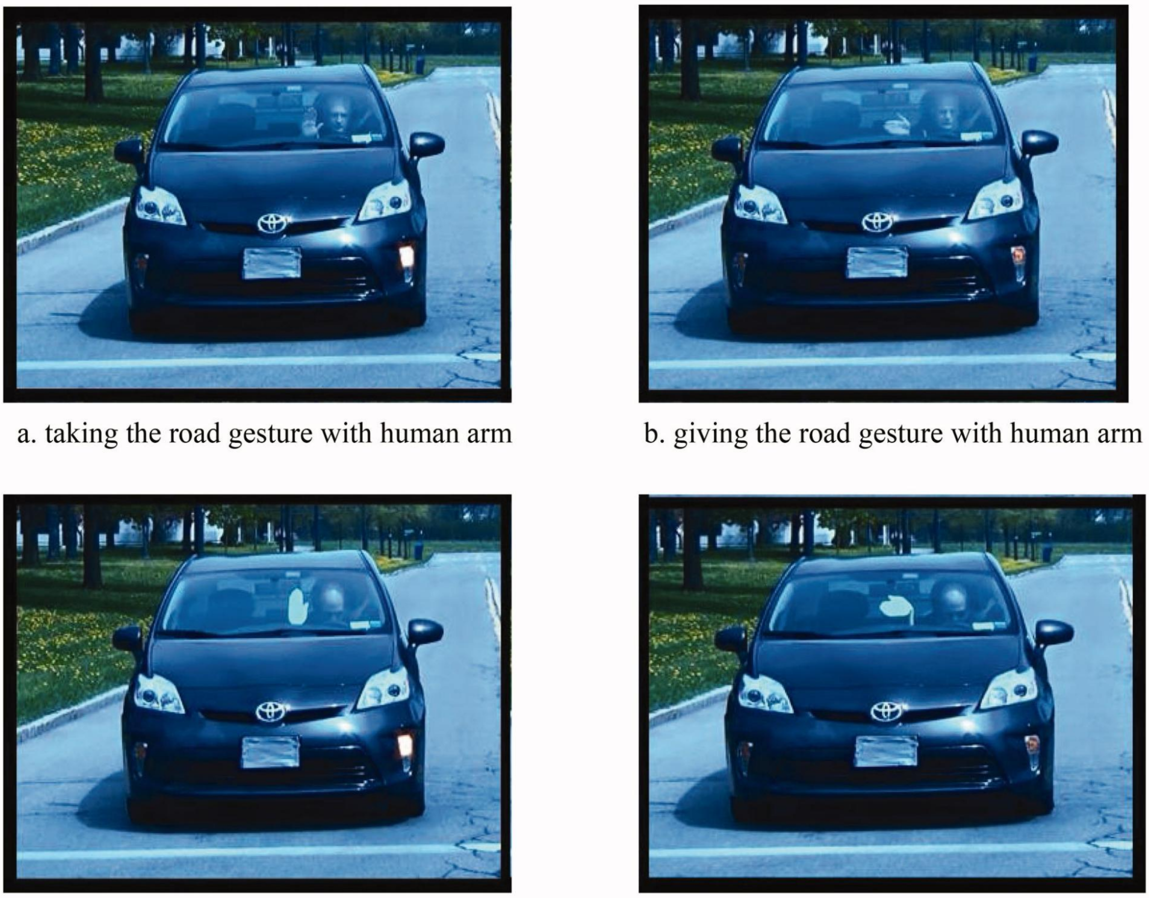
Merge Situations: When a driver is merging, they often rely on non-verbal cues from other drivers to determine when it's safe to merge. For example, a driver might make eye contact with another driver and receive a nod or a wave to indicate that they can merge safely. However, AVs wouldn't be able to interpret these non-verbal cues, potentially leading to confusion or unsafe merging situations.

Pedestrian Crossings: When a pedestrian is crossing the street, they often make eye contact with drivers to ensure that they are seen and that the driver will yield to them (Schmidt and Färber, 2009). However, having chances of the pedestrian in the tunnel is very rare but still that can be counted as an uncertainty for the AVs to communicate.

Changing Lanes: When a driver is changing lanes, they often rely on non-verbal cues from other drivers to determine when it's safe to do so. For example, a driver might make eye contact with a driver in the lane they want to merge into to indicate their intention. An AV might not be able to pick up on these cues, which could lead to unsafe lane changes.

Road Work Zones: In road work zones in the tunnels, construction workers often rely on non-verbal communication to direct traffic safely through the area. For example, a worker might use hand signals to indicate that a lane is closed or that a driver should slow down. An AV might not be able to understand these signals, which could lead to confusion or accidents in the work zone (Färber, 2016).

The probable solution is to develop standardized signage and symbols that are specifically designed for AVs and can be easily understood by human drivers. For example, signs or symbols could be displayed on AVs to indicate their driving mode or their intended maneuver. Such as, if AVs detect someone trying to change the lane then there should be a symbol of accepting the request of changing lanes or giving other drivers a go-ahead signal. In this way, drivers will know that AVs have understood the symbol and it will act accordingly.



a. taking the road gesture with human arm

b. giving the road gesture with human arm

c. taking the road gesture with the mechanical arm

d. giving the road gesture with the mechanical arm

Figure 4.6: Hand Signals for Driving by (Zhang et al., 2022)

Education and awareness campaigns: It's also important to educate drivers and passengers on how to interact with AVs. This could include providing clear instructions on how to signal to AVs, as well as information on the limitations of these vehicles and how they differ from traditional human-driven vehicles.

4.6 Emergency Situations

In addition to these factors, one of the most important factors is emergency situations. There are several specific scenarios in which drivers may exhibit unpredictable behavior in tunnels. These include emergency situations such as a fire or accident, drivers may panic and attempt to exit the tunnel quickly, potentially causing further safety issues. Additionally, the enclosed space of tunnels can impact the ability of AVs to maintain reliable communication with other vehicles, traffic management systems and other infrastructure. This can be problematic in emergency situations, where clear communication and coordination are critical for ensuring safety. At the same time, the survey (Lee et al., 2022) showed that most of the drivers do not have knowledge of tunnel safety equipment in case of emergency. For example, they are not aware of emergency exits, telephones, different evacuation signs, communication channels, how to reverse the vehicle and how to proceed to the U-turn in the tunnel.

A series of studies show that humans underestimated the situation in the tunnels. They showed a difference between what they thought they would do and what actually they have done. In case of an incident, people start behaving differently, some try to exit the tunnel with their cars and some try to retreat in the opposite direction, majority of them try to be in their vehicles and are reluctant to leave their vehicles as others are not leaving their vehicles or they are unsure what to do at that moment despite the given emergency exit signs over their head or with the ceiling (Nilsson et al., 2009). However, if instructions are given to them through the radio or through public announcement (PA) then it has been proven helpful to evacuate. Current data has shown that audio instructions are more effective than visual signs because of smoke (Kobes et al., 2010).

On the other hand, the situation becomes worse when drivers are reluctant to leave their car as it is their property and they find it difficult to retrieve it after the incident so they better try to evacuate the tunnel with the car which creates massive chaos. Studies have shown that two warning signals, audio, and visuals are important to evacuate. In most of the cases, it has been observed that there are some drivers who have seen accidents by visuals like fire and smoke and others got the information about emergency evacuation through radio in the car (Burns et al., 2013). Under smokey conditions, drivers lack visibility and there is a high possibility that they lose their orientation and try to evacuate the tunnel in the direction of the fire source. In that case, visual signs and arrows directing in the exiting directions play an important role during evacuation (Schmidt-Polończyk, 2023).

Figure 4.7: Road Tunnels Solutions provided by Marimils

Fire and life safety systems in tunnels typically involve a combination of different components that work together to detect and respond to potential fire and emergency situations. Some of the key components presented by Mashimo (2002) that represent the basics for fire and life safety systems in tunnels include:

Fire Detection and Alarm Systems: These systems use sensors and alarms to detect the presence of smoke, heat or flames in the tunnel, and provide an audible or visual warning to occupants and emergency responders.

Fire Suppression Systems: Fire suppression systems such as sprinklers or water mist systems can be used to suppress or extinguish fires in the tunnel, reducing the risk of damage and injury.

Fire-Resistant Materials and Construction: Tunnels should be constructed using fire-resistant materials and designs that can withstand high temperatures and prevent the spread of fire and smoke.

Emergency Lighting and Signage: Illuminated signs and exit lighting can help to guide occupants towards emergency exits and evacuation routes in the event of a fire or other emergency.

Ventilation Systems: Proper ventilation can help to prevent the buildup of smoke and toxic gases in the tunnel and improve the visibility and air quality for occupants and emergency responders.

Communication Systems: Effective communication systems are essential for coordinating emergency response efforts and providing timely updates and instructions to occupants and emergency responders.

Emergency Power Systems: Backup power sources such as generators can ensure that critical systems and equipment remain operational in the event of a power outage or other disruption.

Emergency Response Equipment: Tunnels should be equipped with appropriate emergency response equipment such as fire extinguishers, hoses, and other tools to enable occupants and emergency responders to respond effectively to fires and other emergencies (Manca and Brambilla, 2011).

Emergency Access and Egress Systems: Tunnels should have appropriate access points for emergency responders, as well as clear and well-marked evacuation routes for occupants.

CCTV Systems: Closed-circuit television (CCTV) systems can provide real-time monitoring of the tunnel, enabling emergency responders to quickly identify and respond to potential hazards or incidents.

Regular Maintenance and Testing: Regular maintenance and testing of fire and life safety systems is essential to ensure their continued effectiveness and reliability.

Emergency Response Plans and Training: Tunnels should have comprehensive emergency response plans in place, and all occupants and emergency responders should receive regular training and drills to ensure they are prepared to respond effectively to emergencies.

Fire and life safety systems in tunnels are designed to provide a comprehensive and integrated approach to emergency readiness and response, with multiple layers of protection and redundancy to ensure the safety of occupants and emergency responders (Abdul Salam, 2007).

4.6.1 An Evacuation Plan for AVs

An evacuation plan for AVs in the event of a fire in a road tunnel would need to be carefully designed and implemented to ensure the safety of all passengers and other drivers. Here are some steps that could be taken to develop an effective evacuation plan:

Develop Protocols for Vehicle Behavior in Emergency Situations: AVs should be programmed to detect and respond to emergency situations such as fires in tunnels. They should be programmed to immediately pull over to the side of the road and activate hazard lights.

Establish Communication with Emergency Services: AVs should be equipped with communication systems that allow them to communicate with emergency services in case of an emergency. This will help emergency services to quickly respond and provide assistance (Brož et al., 2022).

Identify Safe Evacuation Routes: Evacuation routes should be identified ahead of time and programmed into the vehicle's system. The system should also be designed to automatically identify the safest and most efficient evacuation route in real time based on the location of the fire.

Notify Passengers: The vehicle's system should be designed to notify passengers of the emergency situation and provide clear instructions for evacuation (Burns et al., 2013).

Provide Emergency Equipment: AVs should be equipped with emergency equipment such as fire extinguishers and emergency escape hatches to assist with the evacuation process.

Test the Plan: Once the evacuation plan has been developed, it should be thoroughly tested in simulated emergency scenarios. This will help to identify any weaknesses or areas that need improvement and ensure that the plan can be executed effectively in a real emergency.

Train Passengers: Passengers should be trained on the emergency procedures and evacuation plans for AVs. This should be included as part of the standard safety instructions that passengers receive before using an AVs (Burns et al., 2013) (Kobes et al., 2010) (Schmidt-Polończyk, 2023).

Monitor the Situation: In the event of a tunnel fire, the situation can quickly evolve and change. The AVs' system should be designed to continuously monitor the situation and re-adjust the evacuation plan based on new information.

Collaborate with Emergency Services: Collaboration with emergency services is critical to ensuring a coordinated response in the event of an emergency. AV manufacturers and operators should work closely with emergency services to develop effective evacuation plans, share information and coordinate in response efforts (Brož et al., 2022).

Provide clear Instructions During Emergencies: Clear and concise instructions should be provided to passengers during the evacuation process. This may include instructions on how to safely exit the vehicle, where to go, and what to do next.

Consider the Unique Needs of Passengers: AVs may carry passengers with a variety of physical or cognitive impairments, such as mobility issues or hearing impairments. The evacuation plan should take into account the unique needs of these passengers and provide appropriate accommodations (Kobes et al., 2010) (Schmidt-Polończyk, 2023).

Coordinate with Other Stakeholders: In addition to emergency services, there may be other stakeholders involved in the response to a tunnel fire, such as tunnel operators or transportation authorities. AV manufacturers and operators should work closely with these stakeholders to ensure a coordinated response.

Collect and Analyze Data: In the event of an emergency, it is important to collect and analyze data to identify areas for improvement in the evacuation plan. This data can be used to refine the plan and improve the response to future emergencies.

Conduct Regular Drills and Exercises: Regular drills and exercises should be conducted to ensure that all stakeholders are familiar with the evacuation plan and can execute it effectively (Burns et al., 2013).

Overall, an effective evacuation plan for AVs in the case of a fire in a road tunnel will require careful planning, coordination and testing. The goal should always be to prioritize safety and ensure a timely and effective response to the emergency (Gonzalez et al., 2016). Awareness and education is the only solution to this problem in that case. It's important to establish clear protocols for managing emergencies in road tunnels. This can include procedures for evacuating passengers, managing traffic flow and coordinating with emergency services such as police, fire, and medical personnel (Sarmento et al., 2017).

5 Discussion and Future Work

The outcome of this study has provided valuable information about the challenges of deploying autonomous vehicles (AVs) in road tunnels that are complex and multidimensional, requiring extensive research and investigation. Road tunnels have unique characteristics that introduce a range of compulsions, such as limited visibility, confined spaces and potentially harsh environmental conditions. These factors must be carefully considered in the development and implementation of autonomous systems to ensure their effectiveness and safety within tunnel environments. The existing literature on AVs in road tunnels is limited, indicating a critical gap in current knowledge. This knowledge gap highlights the need for comprehensive studies and empirical research that specifically target the challenges and constraints associated with AVs in road tunnels. It is essential to investigate these areas to gain a deeper understanding of the intricacies involved and to develop effective solutions.

Future research should focus on understanding the impact of tunnel-specific factors on autonomous systems. These factors include varying light conditions, signal interference and limited communication capabilities. Researchers can study these aspects to create better autonomous systems for tunnels.

Another crucial area for research could be the investigation of the influence of tunnel geometries, infrastructure modifications and sensor technologies on the performance and safety of AVs. Tunnel geometries can vary significantly, ranging from narrow passages to large underground caverns. Understanding how these geometries impact navigation, and the performance of AVs is crucial for their successful operation in road tunnels. Over and above that, infrastructure modifications such as improved lighting, signage and communication systems can enhance the compatibility between AVs and tunnel environments.

Sensor technologies play a pivotal role in the functioning of AVs. Research should be conducted to determine the optimal sensor configurations and placements within road tunnels. This will ensure an accurate perception of the surrounding environment, allowing the vehicle to make informed decisions and navigate safely. Not to mention, advancements in sensor technologies, such as improved vision systems and enhanced object detection capabilities, should be explored to overcome the challenges posed by limited visibility and potential obstructions within tunnels.

On this matter, the development of advanced control algorithms and decision-making frameworks is decisive for AVs in road tunnels. These algorithms need to consider the unique dynamics of tunnel environments, which can include factors such as congestion, limited space for maneuvering and emergency scenarios. Robust control algorithms can enable AVs to adapt to these conditions effectively and ensure safe and efficient operations within tunnels.

Along with technical aspects, it is essential to study the human factors involved in the implementation of AVs in road tunnels. Driver interaction and acceptance of autonomous systems within tunnel settings play a significant role in their successful accomplishment. Understanding human behaviors, trust levels and potential challenges in transitioning from manual to autonomous driving modes can provide valuable insights for designing effective human-machine interfaces. This research can help create interfaces that facilitate seamless and intuitive interaction between drivers and autonomous systems, promoting user acceptance and confidence.

Considering the challenges of setting up AVs in road tunnels requires rigorous research efforts. The limited existing literature indicates the urgent need for more extensive and focused investigations in this domain. By conducting dedicated research which aims at the specific constraints and complexities associated with AVs in road tunnels, researchers can develop innovative solutions, advance the state of knowledge and contribute to the successful implementation of autonomous technologies in this challenging and critical context.

Looking ahead, future work should involve conducting comprehensive studies and empirical research to fill the current knowledge gap. Researchers should collaborate across disciplines, including engineering, computer science, psychology, and transportation planning, to tackle the multifaceted challenges of deploying AVs in road tunnels. Furthermore, research should explore topics such as responsibility in accidents, regulation of automated vehicles, societal impact and job displacement. By considering these broader implications, policymakers and industry stakeholders can make informed decisions and create an ecosystem that supports the successful integration of autonomous technologies in road tunnels.

As technology continues to advance and more data becomes available from the operation of AVs, further research can be conducted to gain a better understanding of the effects of AI on congestion, accidents, pollution and other factors. This research will contribute to evidence-based decision-making and help shape policies and regulations that facilitate the widespread adoption of AVs in road tunnels.

The findings presented in this discussion serve as a valuable guideline for various stakeholders, including customers, manufacturers, policymakers and infrastructure managers, in preparing for the future of AVs. It is worth considering not only the technical aspects but also the ethical, social and economic implications of incorporating AI technology in vehicles. Public education and awareness campaigns should be prioritized to ensure that the general public understands the potential benefits and challenges associated with AVs, fostering acceptance and trust.

By continuously investing in research, promoting collaboration and considering the broader implications, we can unlock the limitless possibilities and practical implementations of AVs in everyday life. The deployment of AVs in road tunnels has the potential to revolutionize transportation systems, improve safety and enhance overall mobility. Through dedicated research efforts, the challenges can be tackled; paving the way for a future where AVs seamlessly and efficiently navigate road tunnels, contributing to sustainable and accessible transportation for future generations.

6 Conclusion

In conclusion, the deployment of autonomous vehicles (AVs) in road tunnels presents a multitude of complex challenges that necessitate extensive research and investigation. These challenges stem from the unique characteristics of road tunnels, including limited visibility, confined spaces, and harsh environmental conditions. To ensure the effectiveness and safety of autonomous systems within tunnel environments, careful consideration must be given to these constraints during their development and implementation.

The existing literature on AVs in road tunnels is limited, revealing a critical gap in our current knowledge. This knowledge gap underscores the urgent need for comprehensive studies and empirical research that specifically address the challenges and constraints associated with AVs in road tunnels. By conducting in-depth investigations in these areas, we can gain a deeper understanding of the intricacies involved and develop effective solutions. Future research efforts should focus on understanding the impact of tunnel-specific factors on autonomous systems, such as varying light conditions, signal interference, and restricted communication capabilities. Through comprehensive examination and analysis of these aspects, researchers can develop autonomous systems that are robust, reliable, and tailored to the tunnel environment.

Looking ahead, future work should involve comprehensive studies and empirical research to bridge the current knowledge gap. Collaboration across disciplines, including engineering, computer science, psychology, and transportation planning, is essential to tackle the multifaceted challenges of deploying AVs in road tunnels. Additionally, research should explore broader topics such as responsibility in accidents, regulation of automated vehicles, societal impact, and job displacement. By considering these broader implications, policymakers and industry stakeholders can make informed decisions and create an ecosystem that supports the successful integration of autonomous technologies in road tunnels.

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