An assessment of the potential use of driving simulators for the car-driving test

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By

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Summary

Introduction

Driving is an everyday activity for many people. Therefore, driving licensing programs should train and assess human driving performance to prepare these drivers to drive on the roads independently and safely. The traditional on-road car-driving test aims to contribute to road safety by assessing whether learner drivers can drive safely on the roads.

Driving simulator development is rising these days, and it is getting more and more attention from different research fields, such as road safety research. Safety researchers commonly use driving simulators to examine complex driving behaviors in a controlled and safe environment. The driving simulator has proven valuable as an effective training device for training and learning driving skills like speeding, accelerating, and lane keeping in different driving scenarios. There are also indications about the safety benefits for novice drivers. These drivers are overrepresented in crashes after passing their driving license test. The question remains whether or not a driving simulator could be used to assess novice drivers' driving skills performance. Still, very little is known about driving simulator usage to assess human driving performance in a car-driving test.

This graduation thesis aims to contribute to road safety research by exploring the state-of-the-art of driving simulator usage for a car-driving test. The research explores whether a driving simulator could add value to the traditional on-road car-driving test. This thesis addresses the research question: "*To what extent could driving simulators add value to the traditional on-road car-driving test in order to assess human driving performance?"*

The research used a case study to dive deeper into the different elements of a car-driving test. The Dutch on-road car-driving test is used to explore the potential use of driving simulators for (part(s) of) the on-road driving test in terms of human driving performance assessment. The Centraal Bureau Rijvaardigheidsbewijzen (*CBR*), the Dutch organization for driving licensing, is the organization that has been made responsible for assessing the driving capability of drivers. The CBR divides the on-road car-driving test into seven parts: the start of the driving test; driving on straight and curved roads; driving around intersections; merge and exit on the highway; overtaking and side-way movements; driving at special road intersections; performing special road maneuvers. Each part exists of a set of required driving skills to pass the assessment criteria.

Methodology

A staged research approach of literature research, questionnaire, and in-depth interviews was used to create an information inventory on driving simulator assessment of human driving performance. An overview of the explored information is shown in the conducted research framework. The framework represents a yes/no decision tree that provides an overview of how useful a driving simulator could be for training or testing the required sets of driving skills representing each driving test part. The bottom-up questions refer to what is known about training or testing results using driving simulators. The bottom-down questions represent the usefulness of the found information in comparing them to on-road driving performance. Therefore, the framework considered information about driving simulator results' transferability, reliability, and validity.

The staged research approach started with the semi-structured literature research that was structured using a four-step search plan for sources. For this research, Scopus was used as a literature database. The information from the selected sources was used to fill in the research framework. As a result, the knowledge gaps in the literature became clear for each part of the car-driving test.

The follow-up questionnaire was conducted to gather information from practice to fill in these gaps or add information to what was described in the literature. The questionnaire aimed to use information from experts in driving training and licensing. The International Commission for Driver Testing (CIECA) members were asked to fill in the questionnaire on driving simulator usage experiences. In total, there were 36 members, and 18 responded to the questionnaire, which was a response rate of 50 percent. The questionnaire results showed which members did have practical information on driving simulator usage experience in their driving licensing program. The selected members were: Finland, Estonia, Georgia, and Sweden. Each of the selected members was asked to participate in follow-up interviews. However, due to the time limit of the research and the response time, Georgia was not included eventually, and only Finland, Estonia, and Sweden were available for interviews. The questions asked in the in-depth interviews with the three selected members were based on their information from filling in the preceding questionnaire. As a result, the framework was filled in with information from the literature research and practice. The layered use of research methods resulted in a framework filled in with information for each part of the Dutch car-driving test. The research approach helped to identify the gaps in the literature and practice and showed the state-of-the-art about driving simulator assessment of human car driving performance.

Results

The results of the literature research showed promising results on the usefulness of driving simulators to train overtaking & side-way movements. Based on the literature research information, training results were transferable, reliable, and valid for this part of the driving test. There were no useful training results for the six other parts of the Dutch car-driving test because at least the transferability, reliability, or validity showed negative results compared to the on-road driving performance training results. The literature research found no results on the usefulness of driving simulator test results for each of the seven driving test parts of the Dutch car-driving test. Therefore, the gaps in the literature about driving simulator usage were identified to test the sets of required driving skills for each part of the Dutch car-driving test.

The results gathered from the questionnaire amongst the 36 CIECA members showed that there was just a small amount of practice experience with driving simulator usage in the driving licensing programs. The questionnaire resulted in three selected CIECA members reporting some experiences with driving simulator usage in their driving licensing programs; Finland, Estonia, and Sweden.

The practical information from the in-depth interviews with Finland, Estonia, and Sweden showed that information on the driving simulator's test validity, reliability, and transferability was hard to find. In terms of filling in gaps in the framework for each Dutch driving test part, the interviews did not provide any new information. However, additional information on the usefulness of driving simulator training results related to each part of the Dutch driving test could be added.

Estonia, Finland, and Sweden already use the driving simulator to train in risky driving situations. Estonia uses the driving simulator for nighttime driving, and Finland uses them for slippery track practices. Both countries reported positive experiences with the driving simulator for training hazard perception in these situations. Additional to these findings on simulator training, Sweden reported its belief that the driving simulator could be a promising complement to the actual driving test in terms of testing hazard perception. Therefore, Sweden is researching driving simulator usage as a pre-test to assess hazard perception

Conclusion

The findings of the current research support follow-up research in different research directions. The research aimed to answer the following research question: *"To what extent could driving simulators add value to the traditional on-road car-driving test*?". The study results showed that using driving simulators could lead to a more comprehensive on-road car-driving test regarding hazard perception assessment. Not only could dangerous situations be repeated and tested using different scenarios beforehand, but the divers are actually not exposed to any risk. Sweden even started research in which a driving simulator pre-test for hazard perception assessment is added as a pre-selection to the on-road car driving license test. The Swedish research findings were not yet available. However, based on their experiences with the driving simulator's hazard perception training, a transportable driving simulator without a moving base could be useful for assessing hazard perception. Therefore, this driving simulator type is promising for follow-up research on driving simulator usage to assess hazard perception as part of a car-driving test.

This research also shows promising results for assessing human driving performance while performing "overtaking & side-way" movements on a driving simulator. This part of the driving test seems interesting for further research since the results indicate that driving simulators could be used regarding the transferability, reliability, and validity of human car-driving performance training. According to findings from the literature research, a fixed-base driving simulator with a blind spot could be appropriate.

In conclusion, this research shows promising results indicating the driving simulator's additional value to the on-road car-driving test in assessing hazard perception, overtaking & side-way movements. The results show that simulator-based assessment may be practical, depending on the specific driving task and the type of simulator. However, there is still a significant knowledge gap in driving simulator usage for testing the required skills of the seven different driving test parts of the Dutch car-driving test that could not be solved by this research alone. Even though follow-up research is needed to close the knowledge gap, one should remember that driving simulator assessment may be effective in the future depending on the specific driving task and type of simulator needed.

Discussion

There are some contradictions found in the literature research. Awareness of these contradictions could contribute to future research in terms of identifying the different opinions that could be reflected. First of all, literature research results show that driving simulator usage is rising because of both technological developments and cost reduction. However, essential assessment requirements for the different driving test parts should be considered to create an upswing in using driving simulators for human driving performance assessment related to the on-road car-driving test. The relationship between technological developments and driving simulator usage for particular research purposes is not as straightforward as it seems; it depends on how you define essential realism.

Secondly, two opinions exist in the literature about driving simulator hazard perception. Some researches show a decreased feeling of being at risk while driving on simulated roads. Other researches argue that the simulator is useful for repeatedly testing drivers' hazard perception for risky driving scenarios in a controlled and safe environment. However, the advantages of using a driving simulator to assess hazard perception could outweigh disadvantages like lower realism and reduced field of view. This line of reasoning has been chosen for this research to explore to what extent the hazard perception assessment could probably be improved.

The questionnaire was spread amongst members of the international organization CIECA. It is important that the questions were asked to members from different countries worldwide since the traffic situations and rules are different in other countries. However, of the 36 members of the international CIECA organization, only three countries mentioned that they had any research experience in this field. The lack of experience with driving simulators could be due to two arguments. Both adaptation time and resistance could be reasons for countries that did not even start researching the opportunities to use the driving simulator in their driving training and testing program.

An interpretation of the interview results with Finland, Estonia, and Sweden shows that there is no belief that the driving simulator could replace the traditional driving test on the road despite their positive experiences with driving simulator training usage, like the accuracy of feedback, restrained driving style, and standardizable teaching software. An important counterargument is that driving in a simulator would be hard to compare with driving in the real world. Despite these counterarguments, findings of ongoing research in Sweden led to new insights into developing a more comprehensive driving test using driving simulators to assess hazard perception.

Limitations

The research approach included both types of information from literature and practice. Combining both types of information shows the different research opinions that could strengthen or outweigh each other. It also shows the potential differences between what is stated in literature and what is experienced in practice. The combination of different types of information resulted in a complete overview of what is known in the particular research field of driving simulator assessment of driving performance.

However, there are some limitations related to the chosen research approach. First, the research did not explicitly explore the relationship between the different driving simulator types and their usability for driving performance assessment. Therefore, whether or not a driving simulator could be used for the on-road driving test would require more specific research on a particular driving simulator type that could be used to measure or assess a specific driving skill.

Secondly, since very little research has been carried out about driving simulator usage in assessing driving performance, an explorative research method is used to gather more information. This research method provided new insights into a driving simulator regarding whether or not to use it for the assessment of a driving test. However, this type of research could not find concrete information on the usefulness of driving simulator results regarding transferability, reliability, and validity. Experiments are a better tool to test the usefulness of a specific driving simulator type for a particular assessment purpose like a driving skill.

Finally, this research did not address the topic of simulator sickness. Simulator sickness is a motion sickness that could be present in simulations. The research did not include the absence of simulator sickness as a criterion for the usefulness of driving simulators following the research results in America. The results showed that drop-outs were not the systematically poorest drivers because of driving simulator sickness. The research ensured that driving simulators could assess the performance of drivers who need it the most. However, it is a phenomenon that cannot be ignored completely when possibly implementing driving simulators in the licensing program. Therefore, it is important to consider that simulator sickness depends on the driving simulator type, the particular driving task, and personal characteristics.

Recommendations

Future research should focus on the following combinations of driving simulator types used to assess particular sets of driving skills belonging to the different parts of the Dutch on-road driving-test. The combinations are based on information from the literature research, the questionnaire, and the interviews.

- Start of the car-driving test: A moderate-level recommendation for a fixed-base, high-fidelity driving simulator
- Curved and straight roads: A low-level recommendation for fixed-base, medium- or high-fidelity driving simulator
- Driving at intersections: A moderate-level recommendation for a high-fidelity driving simulator
- Merge and exit on the highway: No concrete recommendation for the driving simulator type
- Overtaking and side-way movements: A high-level recommendation for a fixed-base driving simulator with blind spot
- Special road intersections: No concrete recommendation for the driving simulator type
- Special road maneuvers: No concrete recommendation for the driving simulator type

This research only focused on driving simulator assessment of novice drivers' performance. However, the research findings could also be used for follow-up research on assessing experienced drivers' skills. Regarding the possible contribution to road safety, the research findings of this research should not only be used for novice driving representing a part of the driving population. Thereby, regarding the driving behavior that a subject could show in a driving simulator, getting the subject familiar with driving in a simulator would be recommended.

There are indications from the research practice results of Sweden that the driving simulator could be used as a pre-test to assess drivers' hazard perception before they may start the on-road driving test. It is believed that the driving simulator could be a good complement to the on-road driving test in terms of hazard perception, and its usage could result in a more comprehensive driving test. Based on these research results, follow-up research is recommended to be conducted on developing a valid driving simulator pre-test that could be useful to assess the hazard perception to conduct a more comprehensive car-driving test.

In terms of deploying automated vehicles (AVs), introducing driving scenarios that include these AVs would be recommended in the future. Therefore, setting up the driving simulator-based pre-test for hazard perception assessment could create opportunities to increase the amount of research on the interaction between AVs and other human-driven vehicles when the AVs development is taken into account in the driving simulator scenarios.

Preface

Before you lies the master thesis, " *An assessment of the potential use of driving simulators for the car-driving test.*" The aim was to explore what is known in both literature and practice about driving simulator usage to investigate whether or not driving simulators could be useful in assessing human car driving performance while taking a car-driving test. It has been written to fulfil the master thesis graduation program of Transport, Infrastructure, and Logistics at the Technical University of Delft, the Netherlands.

During my research, I discovered that implementing new technology is complicated and depends on multiple factors that should be considered. Not only are the technical requirements essential but the willingness and interest to use new technology are also as important. The questionnaire results showed that these two societal factors still need to rise beside the technological developments to conduct more research on this topic.

I gained more experience in the field of qualitative research. I was more used to quantitative research before I started my master's thesis, and therefore new skills were required. I learned how to set up sophisticated literature research, which I did not do before in other projects. Since the master thesis covered much longer than other university projects, I learned that struggling is part of the process, and you can learn from it. Improvement of communication skills was part of the whole process as well. I highly value learning to communicate on a more international level, which was needed for the interviews in my research. Sometimes I had to step out of my comfort zone, ask for help, and let my supervisors know what I was struggling with. Therefore, I learned from this thesis both as a person and as a young professional.

This research is hopefully the first step in investigating the additional value the new driving simulator technology could have to implement in a driving test. It would be interesting to see if this research could push other researchers to elaborate on this research topic. If driving simulators could play a significant role in improving road safety in the future would be worth to further investigating as a follow-up to this research.

I hope you enjoy reading.

D.P.E. van Opstal
Delft, February 2023

Contents

Abstract

Car driving is an everyday activity for many people, so the aim is to have a high-quality licensing program. In recent years, driving simulator development has been rising. The driving simulator has proven to be a valuable training tool for human car driving performance. These days, still very little is known about human car driving performance assessment using driving simulators. Therefore, this research explores the state-of-the-art of driving simulator usage for driving assessment. This research aims to investigate whether or not the driving simulator could add value to the licensing program when it is used to assess human driving performance in a driving test. The case study is the on-road car-driving test in the Netherlands, subdivided into seven parts. A framework is used to search for information in literature research and interviews to explore the usefulness of driving simulator results regarding transferability, reliability, and validity. The results show that driving simulators will most likely never replace the current driving test on the road regarding quality improvement of the driving licensing program. However, driving simulator usage can result in a more comprehensive driving test. Using driving simulators to asses " overtaking & side-way movements" shows promising results regarding transferability, reliability, and validity results. Thereby, driving simulators could also add value to the current driving test regarding hazard perception assessment. Since this study is an exploration, follow-up experimental pilot studies are required to validate the research findings.

Acknowledgments

I want to thank Dr. D. D. Heikoop from the *Centraal Bureau Rijvaardigheidsbewijzen* (CBR) for his guidance and support during my research. I highly value how he helped me find direction and clarity during my research. His view on my thesis taught me to assess my work critically. I would also like to thank him for my internship at the CBR, which helped me start my research. I want to thank Dr. J. A. Annema and Dr. E. Papadimitriou from the Technology, Policy, and Management department at the Technical University of Delft for answering my questions and guiding me during the research process. I want to thank Dr. Ir. H. Farah for being the chair of my thesis committee and monitoring how I was doing during the process.

I would also like to thank a few people who helped me gather practical information. To set up the questionnaire and spread it among members of the *International Commission for Driver Testing* (CIECA), I would like to thank a representative of CIECA's Permanent Bureau and one employee of the organization in particular. Regarding gathering practical information, I thank the respondents from Finland, Estonia, and Sweden for responding to the questionnaire and participating in the follow-up interviews. Additionally, I would like to thank an employee of the *Contact Commission of professional drivers Competence (CCV)* and a CBR employee responsible for conducting vehicle driving tests for answering my additional questions about the on-road car-driving test in the Netherlands. I also want to thank another employee of the CCV at the CBR for providing me with interesting insights from the truck driving test in the Netherlands, in which they are also experimenting with driving simulators.

Last, I would like to thank my family and closest friends for supporting me during the research period.

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List of acronyms

CBR	*Centraal Bureau Rijvaardigheidsbewijzen, the Dutch organization for driving licensing*
CIECA	*International Commission for Driver Testing*
VDAB	*Vlaamse Dienst voor Arbeidsbemiddeling, Flemisch Employment Services*
CCV	*Contact Commissie Vakbekwaamheid Chauffeurs, the Contact Commission of professional drivers Competence provides the exams for professionals in road transport, inland shipping, and logistics, tests the theoretical knowledge of professional and private pilots*
TBT	*Toets Besloten Terrein, this driving test does assess the driving skills of performing special maneuvers of truck drivers while driving on a closed-off terrain for other traffic users*
AVs	*Automated Vehicles*
HPT	*Hazard Perception Test*

1. Introduction

Car driving is an everyday activity for many people and is considered a safety-critical task (De Winter et al., 2008). One of the main factors influencing traffic safety is road users' driving behavior (Rosolino et al., 2014). This driving behavior is assessed in an on-road driving test before drivers can drive independently in the Netherlands (CBR, n.d.-c). For this research, the driving behavior performance in a driving test is expressed as "driving performance." The driving performance assessment in the on-road driving test is supposed to be a screening on whether a candidate can drive safely on the road as an independent driver. The on-road driving test aims to contribute to maintaining road safety.

In recent years, driving simulators have attracted increasingly particular interest from traffic safety researchers to explore and study the influence of human factors on road safety (Meuleners & Fraser, 2015; Pawar & Velaga, 2022). Flight simulators have proven to be an effective training tool for enhancing safety (Hirsch et al., 2016). Aviation safety has been enhanced via pilot and crew training in flight simulators. More recently, the combination of cost reductions and technological developments has made using simulators for driving simulation-based training more feasible (Hirsch et al., 2016). Most drivers receive formal on-road training before taking a car-driving test and obtaining their driving license to be allowed to drive on public roads. The potential of driving simulator training benefits holds promise for road safety. Driving skills learned on a driving simulator could successfully be transferred to the driving test performance (Hirsch et al., 2016).

The driving simulator could be an effective training device for driving skills to improve road safety. Based on the comparisons between training results on the road and on a driving simulator, the simulated world seems to have advantages regarding road safety. Providing a safe training environment, repetition of driving scenarios, and controlling variables that define the environmental scenarios, are benefits compared to the real road. Regarding these safety benefits of driving simulator training results, it would be interesting to train on a driving simulator and see if there is potential for driving skills assessment. Since the driving test assesses whether drivers can independently drive safely on public roads, the driving simulator could add value to this assessment. However, still very little seems to be known about driving simulator usage for driving skill assessment in a car-driving test.

This research aims to create an inventory of the state-of-art driving simulator usage for a car-driving test. The research uses information from literature and practice to fill in a framework created to find information about the potential usefulness of driving simulator assessment results for driving skills. The research is focused on the on-road car-driving test in the Netherlands since it is conducted for the Dutch Driving Test Organization (*CBR*). In the Netherlands, learning drivers have to complete an official test before they are legally allowed to drive a car on the road. The CBR assesses whether learning drivers can safely participate in traffic situations on the real road (*About CBR*, n.d.). Paragraph 1.1 elaborates on the knowledge gap. The research question that results from the research gap is explained in paragraph 1.2. The sub-questions used to answer the research question are described in paragraph 1.3. The explanation of essential factors determining the research angle in terms of searching for information on the usefulness of driving simulator assessment results is written in paragraph 1.4.

1.1 The knowledge gap

Interest in the development of driving simulators has been rising. Driving simulator usage has become more commonplace (Shechtman et al., 2009; De Groot, 2013). Technological advancement has been one of the reasons for the rising interest in driving simulators (De Winter, 2009). New technologies resulted in driving simulators that better resemble real-world driving regarding the visual environment and vehicle controls (Wynne et al., 2019). The other reason for the rising interest is the cost reduction of driving simulator development (Eryilmaz et al., 2014; Hirsch et al., 2016).

In recent years, researchers commonly use driving simulators to examine complex driving behaviors in a controlled and safe environment (Wynne et al., 2019). The driving simulator measures the driving performance in an environment highly similar to the actual driving task (Van Emmerik & Kappé, 2005; Kappé et al., 2009). An example of successful simulator usage can be found in the use of flight simulators to train flight skills. It proves the flight simulator's value as an effective training tool and significantly improves flight safety (Allerton, 2010). Even though there is less experience with driving simulators than flight simulators, using driving simulator-based training has become more feasible recently (Hirsch et al., 2016). Compared to on-road car training, the driving simulator has some advantages. Training on driving simulators provides a safe environment to practice maneuvers, even dangerous ones, and the learning space can be controlled, and scenarios can be repeated (Hirsch et al., 2016). Sætren, Birkeland, Pedersen, Lindheim, & Skogstad (2019) argue that driving simulators do not only have the potential to optimize the driving training program but could even contribute to safer roads. If this contribution to safer roads could be accomplished, the driving simulator could be of great societal relevance since car driving is an everyday activity for many people.

Driving a car is a complex task that requires many different driving skills (De Winter et al., 2008). Therefore, it is of great importance that drivers on the road can drive safely. However, (young) novice drivers who just passed their driving license test are over-represented in crashes (European Commission, 2021). These young drivers do have more risky behavior due to overconfidence during driving. They lack high-order driving skills and hazard perception (European Commission, 2021). The over-representation of these novice drivers is an issue that has already persisted for a long time (Elvik, 2010).

Most European countries have included a learning period in their driving license program in which drivers can drive with an experienced accompanying driver before the final driving test. Unfortunately, the crash risk of novice drivers is the highest in the months after passing the driving test (European Commission, 2021). In terms of improving these crash risks of novice drivers, there has been an indication that simulator usage in the driving license program might create safety benefits for novice drivers from the moment they begin driving independently (Rodwell et al., 2019; Sætren, Birkeland, Pedersen, Lindheim, & Skogstad, 2019). However, using driving simulators is a relatively new phenomenon requiring further investigation (Wynne et al., 2019). It would be interesting to investigate whether or not the driving simulator could be used not only for training but for assessment of these human car driving skills as well. Still, very little is known about driving simulator usage to assess car driving performance.

To investigate the potential use of driving simulators to assess driving skills, this research uses the factors described by Blana (1996) to define the quality and usefulness of driving simulator assessment results. Transferability, reliability, and validity of simulator results are searched for regarding driving simulator assessment of human car driving skills. These three factors could provide more information to indicate whether or not driving simulators could be used to assess human car driving skills in the future. Further elaboration on these factors is written down in paragraph 1.4.

1.2 Problem statement

In recent years, driving simulators have attracted increasing interest (Shechtman et al., 2009; De Groot, 2013). They have become a more commonly used training and research tool (Wynne et al., 2019). The driving simulator has proven its value as an effective training device for training and learning driving skills, but there are also indications about the safety benefits for novice drivers. The question remains whether or not a driving simulator could be used to assess novice drivers’ driving skills performance. To the researcher's best knowledge, using a driving simulator to assess human car driving skill performance is a new phenomenon requiring further research. Therefore, this research explores the potential use of driving simulators for (part(s) of) the Dutch practical driving test in terms of driving performance assessment.

This thesis addresses the research question: To what extent could driving simulators add value to the traditional on-road car-driving test in order *to assess human driving performance?*

1.3 Research questions

There are three sub-questions formulated to support this main research question. These sub-questions ensure that the research steps are taken to provide an answer to the main research question. Definitions used in these research questions are explained in the next paragraph, 1.4. The sub-questions that will be answered during the research report are:

1. *What is known from scientific literature research on transferability, reliability, and validity of driving simulator assessment results for human car driving performance?*

This sub-question will be answered in the literature research in chapter 3 of this thesis. The answer to this question provides an overview of the information available from the literature for each part of the Dutch on-road car-driving test.

2. *What information could be derived from practical research on transferability, reliability, and validity of driving simulator assessment results for human car driving performance?*

Not everything that is researched is written down in literature. Some research or experiences with driving simulator usage could be done without mentioning that in the literature. Therefore, practical data is gathered by answering this research question as additional information to what is found in the literature research. Chapter 4 of the thesis report will answer this research question. The chapter describes the results of a questionnaire and follow-up interviews among experts in driving training and testing.

3. *How could a driving simulator test human car driving skills performance to asses driving tasks?*

The on-road car-driving test in the Netherlands is used as a case for the research evaluation. The driving performance assessment during this car-driving test is divided into seven elements determined by "The Centraal Bureau Rijvaardigheidsbewijzen" (*CBR*). These seven elements are described in paragraph 1.5.

Each part of the driving test exists of driving tasks that include a set of required driving skills that are assessed. This sub-question determines whether the information is available on the most detailed level of research on driving simulator assessment. If no information on the driving task is available for one or more predefined parts of the Dutch driving test, information about a particular driving skill could be available instead. This sub-question is be answered by both research method results from chapters 3 and 4.

The answers to the three sub-questions are combined to conclude the driving performance results when performing a driving test on a driving simulator. As a result, the main research question is answered.

1.4 Definitions from research questions

This paragraph explains the definitions used in the research questions in more detail. Additionally, the three critical factors defined by Blana (1996) to determine the quality of the driving simulator assessment results are described.

Driving simulator

Generally, a driving simulator is a technical device in which a driver can drive a vehicle in a simulated world instead of on the real road (Blana, 1996a). Regarding the research context, driving simulator usage is explored for driving performance assessment in the seven parts of the Dutch on-road car-driving test.

Driving performance

The driving performance can be described using a set of parameters that together indicate the performance of a particular driving element. The research of Papantoniou, Papadimitriou & Yannis (2017) measures driving performance regarding driver distraction. Regarding the research purpose of this thesis, the driving performance is expressed in the set of driving tasks that must be completed successfully for the seven driving test parts together. In other words, the driving performance includes the performance on the seven parts of the on-road car-driving test in the Netherlands.

Driving task

The primary driving task is driving a car (Wester et al., 2008). This research only focuses on describing this primary driving task and not on secondary tasks like conversations with another passenger during driving. In this research context, car driving is described according to the seven parts of the traditional on-road car-driving test. The seven parts of the on-road car-driving test in the Netherlands are described as one or a few driving task(s) that must be completed. The definition of the driving tasks will be described in chapter two.

Driving skill

Driving a car is a complex task involving several skills simultaneously (Wester et al., 2008). For this research, a driving skill is indeed defined as a part of the driving task. Proper execution of a driving skill is required to complete the driving task during the driving test successfully. The driving skill is defined as the level of detail that is measurable. Therefore, this research explores whether or not the driving simulator can measure a particular driving skill to provide insights into the assessment possibilities of the performance on driving tasks.

Driving simulator transferability, reliability & validity

The definitions are determined as the ones used by Blana (1996a):

- "*The transferability*" is whether or not the results from the simulated environment could be transferred to the real traffic environment. For example, when a driver faces the same traffic situation determined by a set of priority rules on the real road, he should act the same in the predefined scenario on the driving simulator.
- *"The reliability"* is the consistency with which a test measures what it measures. In other words, whether or not there is consistency between real road and simulator test scores. The research findings should be repeatable. An example of a reliable tool is a medical thermometer since it measures the correct body temperature every time it is used.
- *"The validity"* of a test is defined as the extent to which it measures what it is supposed to measure. For example, if the test is designed to measure a person's intelligence, it should not measure something else, like a person's memory.

The three factors provide insight into whether or not driving simulator test results are useful in adequately assessing driving performance compared to the real road.

2. Research context

This chapter describes the context of the research. The car driving licensing program in the Netherlands is explained in paragraph 2.1. The seven parts of the on-road car-driving test are described in their assessment criteria. Paragraph 2.2 provides an in-depth description of the quality of the driving simulator assessment results regarding validity, reliability, and transferability. The quality of driving simulator assessment results also depends on different driving simulator types that could be used. Paragraph 2.3 elaborates on the driving simulator types. In the last paragraph of this chapter, each driving test part is described as a set of driving tasks for which particular driving skills are required.

2.1 The on-road car-driving test set-up

Everyone who wants to drive a motor vehicle on the road must have a driving license in the Netherlands. Therefore you must pass the driving test. The test is also called "the fitness to drive" test. In other words, the test is meant to determine whether or not candidates could safely participate in traffic situations in which they are participating individually (Van Emmerik & Kappé, 2005). The Centraal Bureau Rijvaardigheidsbewijzen (*CBR*), the Dutch organization for driving licensing, is the organization that has been made responsible for assessing the driving capability of drivers. It is a public-law independent administrative body that the government has given the traffic safety responsibility. Thereby, the CBR works with other organizations on an international level on traffic safety and harmonization of traffic regulations in the EU (CBR, n.d-c.).

A tiered approach is used in the Netherlands to get your driving license. The first step is a theoretical driving test (CBR, n.d.-b). The theoretical test has to be taken at a CBR location. The total duration period of the test is 30 minutes. During the test, a candidate must show that he knows the traffic rules and how to handle different traffic situations. Thereby, the hazard perception is tested using multiple scenarios. Three parts could officially be distinguished. "Hazard perception" does contain 25 questions, of which the candidate should have at least 13 correct answers. The second category does contain 12 knowledge questions, of which the candidate should answer ten questions correctly. The third category of 28 questions about what to do in different traffic situations is called "traffic insight." At least 25 questions should be answered correctly for this category. If the candidate passes all three parts, he passes the theoretical driving test.

After passing the theoretical driving test, a candidate can go to the next step in the driving licensing program, which is the practical driving test (CBR, n.d.-a). The candidate has to drive on the road for around 30 minutes with an official examiner who assesses different aspects of the driving performance. The total duration of the practical driving test is 55 minutes. The examiner assesses various aspects of driving, like car handling skills, gaze behavior, and applying traffic rules (Van Emmerik & Kappé, 2005). The driving test exists of three parts. Before starting the drive, the candidate and examiner meet each other on the test terrain.

Additionally, the examiner asks a few questions about the car itself. The candidate must also pass an eye test before stepping into the car. The drive takes 35 minutes, in which the candidate has to drive from the starting point to a particular destination and then back to the starting point again. During the drive, the examiner assesses the driving performance of the candidate. After returning to the test terrain, the examiner tells the candidate if he passed or failed the driving test, and he provides context for the decision.

Both tests (practical and theoretical) should fulfill specific criteria. The most important two are validity and reliability (Van Emmerik & Kappé, 2005). Both requirements are explained in further detail for the practical driving test in paragraph 2.2.

The Dutch on-road car-driving test is subdivided into seven parts (CBR, n.d.-a):

- Start driving test
- Driving on straight and curved roads
- Driving around intersections
- Merge and exit on the highway
- Overtaking and side-way movements
- Driving at special road sections
- Performing special road maneuvers

For each part of the driving test, both a description and assessment criteria are shown in Table 1. The assessment criteria are the basis for the driving tasks and skills required for each part of the driving test, which will be elaborated on in paragraph 2.4.

Table 1
The seven parts of the Dutch on-road car-driving test

Caption	Driving test part	Assessment criteria
Start driving test	Start of the driving test when the candidate starts the vehicle and drives away from the parking spot.	- Vehicle handling under control - Looking around and gaze behavior that is safe for the surrounding traffic
Straight & curved roads	The candidate has to drive straight and curvy roads. These are roads without crossing vehicles from other directions.	- Keeping enough space in front, behind, and next to the car - Drive with the traffic flow - Detect hazards on time
Intersections	The candidate has to interact with vehicles crossing the driving lane.	- When approaching a cross-section, look forward and adjust your speed - Comply with the traffic rules - Safe gaze behavior - Make clear to other road users what your driving moves will be
Merge & exit on the highway	The candidate should be able to merge and exit on the highway. The candidate is being asked to drive on the highway during the driving test.	- Safely looking around and forward - Timing of merging or exiting with the right speed - Be no obstruction for other traffic
Overtaking & side-way movements	The candidate should be able to overtake and change lanes while traffic approaches from the opposite direction or behind.	- Do not obstruct other road users - Safe gaze behavior and looking around at the right time - Let other road users know on time what your driving movements are
Special road sections	There are special road sections that the candidate could have to deal with during the drive, for example, pedestrian crossings, railroad crossings, and bicycle crossings.	- Gaze behavior - Following the priority rules correctly
Special maneuvers	The candidate should be able to conduct two of these special maneuvers during the driving test. For example, reversed driving or parallel parking.	- The special maneuvers should be conducted in a safe space on the road - The maneuvers should be safe for other road users - Vehicle handling under control - Safe gaze behavior and take into account other traffic

2.2 Driving simulator transferability, reliability & validity

Blana (1996a) argues that the results should be transportable, trustworthy, and valid between the simulated and real-world driving performance assessment to evaluate the usefulness of driving simulator results.

Whether or not the driving simulator results are contradictory between the simulator and the real world depends on transferability. The driving performance results on the simulator should also be found on the real road when the same traffic circumstances occur. For example, a driver facing a particular intersection while driving in a simulator should perform comparably when facing the same intersection on a real road.

The reliability of driving simulator results is significant since it shows whether or not there is consistency between test results. Driving simulator results that are found should not be random but repeatable. There are two kinds of reliability, behavioral and physical (Blana, 1996a). The physical reliability of the sub-systems of the driving simulator could easily be tested. However, behavioral reliability is more challenging to measure or identify. This reliability type could be related to different motivations and attitudes towards the driving simulator compared to driving on the road.

Even more critical than the reliability of a driving simulator is its validity. Valid driving simulator results show that the driving simulator assesses the driving performance and not something else unintentionally. For example, the driving simulator should not allow drivers to get used to certain predefined driving scenarios and act based on repetition instead of using driving skills.

There are different types of driving simulator validity. The relevant types for this research are shown in figure 1.

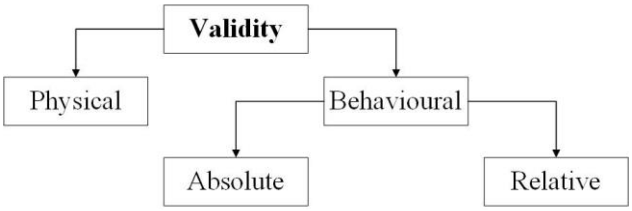

Figure 1
Validity categorization
Note. Own source (2022)

Since this research focuses on the simulator assessment of driving performance to investigate whether or not the simulator results are usable, “relative validity” is chosen as a critical value for this research. On the one hand, “physical validity” includes comparing the simulator and actual vehicles (Blana, 1996a). On the other hand, there is “behavioral validity,” which means measuring physical/mental workload and comparing the simulator and the road during identical circumstances in terms of performance. Since it is sufficient in most cases to determine relative validity, this research only focuses on investigating this type of validity. Behavioral validity can be divided into " absolute and “relative validity.” According to Blana (1996a), absolute validity is a quantitative criterion in which the numerical values of the driving performance differences are equal. However, this type of validity is hard to achieve. Therefore, Blana (1996a) defines relative validity as a “qualitative criterion” achieved when the performance differences of a subject driving on the real road and the simulator under similar conditions are of the same order and direction.” This type of validity is a more achievable criterion and therefore assumed to be sufficient to determine whether or not the simulator is valid when used for assessment (Blana, 1996a).

Concerning the driving simulator validity, there is an adaption period for drivers to adapt to driving simulator usage. This adaptation period could significantly influence the simulator's validity (Ronen & Yair, 2013). The switch between driving on the road and in a simulator does require the transfer of motor-cognitive skills to operate the simulator correctly. Additionally, cognitive and behavioral skills should be transferred to act and react appropriately in the simulated environment (Ronen & Yair, 2013). The arguments by Ronen & Yair (2013) show that simulator validity is not an independent research phenomenon.

Introducing the driving simulator in the driving license test would indicate changes compared to the traditional situation in which the actual driving car is used. Therefore, the interaction of learning drivers and instructors with the driving simulators is essential to predict their interaction with this new technology in a driving test. These perceptions of learning drivers and driving instructors are necessary to ensure that the driving simulators can be adopted effectively in the driving test (Rodwell et al., 2019).

In other words, the effectiveness of using a driving simulator for the driving test depends on the internal and external characteristics of the driving simulator. Internal characteristics are the transferability, reliability, and validity of driving simulator results. The adaptation period and perceptions about driving simulators are external characteristics that should be considered.

The driving simulator validity, reliability, and transferability are accounted for in the framework that is used for this research (paragraph 3.2.1). The framework evaluates whether or not the driving simulator results found in literature and practice are transportable, trustworthy, and valid regarding exploring driving simulator usage for driving performance assessment.

2.3 Fidelity levels of driving simulator

The simulated world is not the same as driving in the actual world. Therefore, a factor that will remain important when using driving simulators is the "simulator fidelity." In other words, the degree of realism. However, the complexity of the real world is too difficult to simulate (Van Emmerik & kappé, 2005). Since the simulator could not imitate the real world perfectly, their degree of realism is expressed in "physical fidelity" (van Leeuwen et al., 2015). Physical fidelity is defined by visual factors, vehicle interior, and software characteristics (van Leeuwen et al., 2015). Therefore, the field of view, the dashboard design, and the dynamic vehicle model are essential. Technological advancements have increased fidelity for visual factors like the field of view and resolution (van Leeuwen et al., 2015). The dynamic vehicle model is divided into vehicle and traffic models. The vehicle model simulates the movements of the own vehicle. The input is delivered by the driver's performance on steering wheel movements, pedal, and gear stick usage (Van Emmerik & Kappé, 2005). On the other hand, the traffic model generates the surrounding traffic since driving a car is a complex task in a dynamic environment (Van Emmerik & Kappé, 2005).

Understanding and comparing driving simulator capabilities increases the need to classify them (Eryilmaz et al., 2014). There are challenges to be expected for control features in the simulator mock-up, vehicle movements, and visual information (Van Emmerik & Kappé, 2005). Figure 2 (*VS600M Truck Simulator by Virage Simulation*, n.d) shows an example of a mock-up in which a person has to drive a simulated vehicle. The type of mock-up depends on the particular driving simulator that is used. A standard set-up mainly contains steering powers, pedals, a gear stick, and a dashboard. The level of realism of each vehicle element does determine the fidelity level of the simulator that is used.

Figure 2
Driving simulator mock-up
Note. Copied from VS600M Truck Simulator by Virage Simulation (n.d.)

The impact of different levels of fidelity on driving performance is essential to investigate during this research because it is often argued that driving simulators need to be sufficiently realistic (Kaptein, Theeuwes & van der Horst, 1996). However, sometimes, deviation from reality could result in a more realistic driving performance (van Leeuwen et al., 2015). The choice to determine a certain level of fidelity is not based on a standardized method with detailed criteria that can be found in the literature. A limited amount of studies is related to the fidelity classification of driving simulators (Eryilmaz et al., 2014). The few studies used costs, purpose, or visual and sound systems as features for classification. The study of Blana (1996a) used a three-level fidelity classification based on the costs of driving simulators. However, this classification does not consider any actual properties of the driving simulator. It considers a low-medium-high staged fidelity. Allen and Tarr (2005) also classified simulators into four levels (1 to 4). However, their classification was inadequate since it only targeted specific simulators and did not define criteria explicitly. Blana (1996b) conducted another study on driving simulators in which classification was based on their use. The research of Lang et al. (2007) did add dimensions related to simulator training goals for classification. The classification classes were explained in detail. However, simulator criteria were not explicitly defined. The study of Eryilmaz et al. (2014) did provide a classification method based on categorization standards for motion, visual, and sound systems designed for simulated helicopter flight training equipment. This study did evaluate and categorized criteria according to their relevance for driving simulators. The study conducted a comprehensive list of criteria aggregated for truck driving simulators and could be used for all driving simulators. The relevance of the study of Eryilmaz et al. (2014) is that it could provide an overview of several cost-effective competent simulators to train and license drivers for specialized driving activities. Therefore, the driving simulator classification by Eryilmaz et al. (2014) is used in this research. Since the focus of this research is not to investigate the technical details of driving simulators, the driving simulator classification of the study of Eryilmaz et al. (2014) is simplified to a lower level of detail for this research. The classification in Table 2 describes what type of simulator could be used for different parts of the on-road car-driving test.

Table 2
Driving simulator classification

Driving simulator class	Elements of driving simulator design	Motion	Visual	Sound
High fidelity	- Control panel lighting - Driving test data validation - Instructor controls - Tire failure models - Extensive self-testing	- Vehicle characteristic vibration and effects	- Advanced scene features (visual cues accurately representing reality)	- Acoustic environment (tested for realism)
Higher medium fidelity	- Vehicle cabin and control panel - Navigation equipment - Instructor seat capability	- Motion platform - Motion cues - Spatial driving effects	- Daylight, night, and visual scenes - Visual database	- Sound of windshield wipers, wheels, and braking
Lower medium fidelity	- Vehicle dynamics modeling - Environmental modeling - Instructor seat visibility	- No requirements	- Visual cues - System brightness and contrast setting	- Cabin sounds
Low fidelity	- Cabin equipment and mirrors represented - Control forces on the vehicle	- No requirements	- Basic visual capability	- Engine, transmission sounds

Note. Copied from Eryilmaz et al. (2014)

2.4 Driving performance: driving tasks & skills

This paragraph describes the seven parts of the Dutch driving test (Table 1) in more detail. The focus of this research is on exploring driving simulator usage for the assessment of human car driving performance. The driving performance is determined as the human car driving performance on each of the seven on-road car-driving test parts. These driving test parts are described in more detail by dividing them into driving tasks that must be completed successfully. The assessment takes place by defining these driving tasks on a more detailed level, namely driving skills. Table 3 shows the driving tasks and required driving skills for each of the seven parts of the driving test. The literature research and in-depth interviews search for information on all detailed levels. The research framework in paragraph 3.2.1 shows these different levels of detail for both research methods.

Table 3
The seven parts of the Dutch on-road car-driving test: subdivision in driving tasks and driving skills

Driving test part	Driving task	Driving skill
Start driving test	- Vehicle handling - Interact safely with surrounding traffic	- Clutch control (Lu et al., 2012) - Brake pedal performance: force, distance, and timing of brake (Rangesh & Trivedi, 2019) - Speed control: lateral and longitudinal (Wang et al., 2010) - Acceleration control: lateral and longitudinal (Wang et al., 2010) - Gaze behavior control: # short glances and # long lasting glances (Wang et al., 2010)
Straight & curved roads	- Distance keeping towards other vehicles - Traffic flow compliance - Hazard detection	- Speed control: lateral and longitudinal (Wang et al., 2010) - Acceleration control: lateral and longitudinal (Wang et al., 2010) - Distance control: meters to other vehicles longitudinal and lateral (Blana & Golias, 2002)
Intersections	- Forward-looking & speed adjustment - Comply with priority rules - Interaction keeping with other traffic	- Speed control: lateral and longitudinal (Wang et al., 2010) - Acceleration control: lateral and longitudinal (Wang et al., 2010) - Gaze behavior control: # short glances and # long lasting glances (Wang et al., 2010)
Merge & exit on the highway	- Timing of merge and exit - Considering other road users to avoid obstruction	- Lane positioning: distance to edges - Speed control: lateral and longitudinal (Wang et al., 2010) - Acceleration control: lateral and longitudinal (Wang et al., 2010)
Overtaking & side-way movements	- Timing and communication of driving movements - Considering other road users to avoid obstruction	- Control of the following distance: longitudinal (Pawar, Nagendra & Velaga, 2021) - Speed control: lateral and longitudinal (Wang et al., 2010) - Acceleration control: lateral and longitudinal (Wang et al., 2010)
Special road sections	- Following priority rules - Interaction keeping	- Gaze behavior control (Dozza et al., 2020) - Speed control: lateral and longitudinal (Wang et al., 2010) - Acceleration control: lateral and longitudinal (Wang et al., 2010) - Compliance with priority rules (Landry et al., 2018)
Special maneuvers	- Vehicle handling - Safely perform maneuvers in terms of other road users - Perform parallel parking - Perform reversed parking - Perform uphill parking	- Gaze behavior control: # short glances and # long lasting glances (Wang et al., 2010) - Clutch control (Lu et al., 2012) - Brake pedal control: force, distance, and timing of brake (Rangesh & Trivedi, 2019)

The driving tasks and skills shown in Table 3 above are not predefined. Most driving tasks and skills could be applied to each driving test part. However, this research distinguishes the main focus of each driving test part, meaning that only driving tasks and skills that define the primary purpose are written down in the table to create a clear distinction in the search for information.

3. Methodology

The methodology is a staged approach with sequential steps to gather the data. Paragraph 3.1 defines the literature research, questionnaire, and interviews as three different research methods within the staged research approach. The paragraph elaborates on combining these two methods to gather the data. The literature review, questionnaire, and interviews are each sequentially described in sections 3.2 until 3.4. Paragraph 3.2.1 elaborated on the created framework. This framework served as a tool to provide a structure for exploring driving simulator usage to assess human driving performance in a car-driving test. The framework content aims to create a purpose-specific search in literature to what is known about driving simulator usage for driving tests. The information from the questionnaire and follow-up interviews should be added to the information from the literature research to fill in the gaps in the framework. Paragraph 3.5 shows an example of the framework application used during this research.

3.1 Methods of data collection

A combination of three research methods gathered data about driving simulator usage for assessing human driving performance on a car-driving test. In sequential order, these methods gathered the available data on driving simulators. The data of the three research methods were a combination of both theory and practice. The theoretical data provided an overview of what research on driving simulator usage has been published. The practical data were used to give an overview of the research information that was not published. Together, the three research methods contributed to a data overview of theoretical and practical data to evaluate what is known about driving simulator usage for a driving test.

The first research method was literature research. The input for this method was a set of keywords that defined a selection of articles. Then, a framework was developed to structure the search for relevant articles. This framework should be filled in with information. The framework shows which information was available in the literature and which was not. Therefore, the output of the literature research is the input for the following research method, the questionnaire.

The second research method was a questionnaire. The questionnaire was for an expert driver training and licensing organization, the *International Commission for Driver Testing* (CIECA). The output was practical data about simulator usage for driving tests that referred to the knowledge and opinions of multiple countries worldwide. The third research method existed of interviews. The selection of countries to which follow-up questions were asked was based on the questionnaire's answers. The answers and opinions of the different countries that responded to the questionnaire were the input for specific questions in the interviews.

3.2 Semi-systematic literature research

Literature research is selected to gather information from research done and written down in literature about driving simulator usage for driving tests. Therefore, finding research articles about this topic and providing an overview was the primary goal of literature research. As a result, semi-systematic literature research was selected. Semi-systematic literature research enables the achievement of overviewing the research topic about driving simulator usage for driving tests. This type of research often looks at how research within a selected field has developed over time (Snyder, 2019). For this research, it was helpful to see how research on driving simulator usage developed to create an overview of what has already been researched and what still needs to be researched today.

A self-made search plan has defined the structure used to search for relevant articles. This plan has four main steps and has been executed separately for each of the seven parts of the driving test. Figure 3 shows the four main steps of the search plan.

1. Determination of the first set of keywords
2. Determination of additional keyword (s) via snowballing
3. Searching other sources via backward and forward search
4. Create an overview of the found references on the research topic

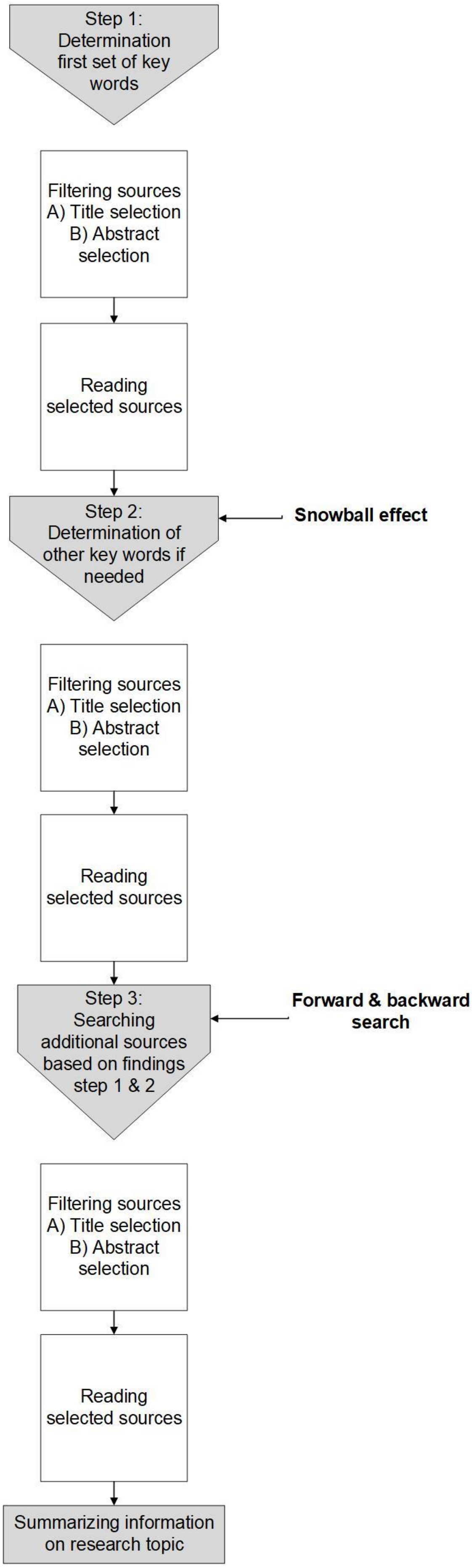

Figure 3
Search plan for semi-systematic literature research

The researcher determined the first set of keywords based on pre-knowledge about the research topic. The second set of keywords resulted from snowballing. The keywords were different for each of the seven driving test parts. Table 4 presents the sets of keywords.

Table 4

Overview of keywords for each driving test part during the several steps of the search plan

Research subject	**Keywords step 1**	**Keywords step 2**	**Total number of useful sources**
Start driving test	Driving AND simulator AND accelerator AND control*	Driving AND simulator AND static AND environment Driving AND simulator AND mirror AND gaze AND behavior Driving AND simulator AND gear OR gearshift AND performance Driving AND simulator AND acceleration AND control AND vehicle Driving AND simulation AND clutch AND performance	5
Driving on straight & curved roads	Driving AND simulator AND straight	Turn AND maneuvers AND driving AND simulator	11
Merge & exit on the highway	Highway AND merging AND driving AND simulator	Highway AND exit AND driving AND simulator	4
Overtake & side-way movements	Overtaking AND mirror AND check AND driving AND simulator	Change AND lanes AND driving AND simulator AND performance	4
Special road maneuvers	Parking AND simulator Uphill AND driving AND simulator	Reverse OR parallel AND parking AND simulator	4
Behavior near and around intersections	Simulator AND driving AND road AND intersection AND behavior	No other keywords were found that provided new relevant sources	6
Behavior near and around special road sections	Pedestrian AND crossing AND driving AND simulator Railroad AND crossing AND driving AND simulator Bicycle AND crossing AND driving AND simulator	Vehicle AND conflict AND crossing AND simulator	5

* Step 1, “start driving test,” did not directly result in any useful articles for this topic. Therefore, starting a car had been divided into four sub-categories: acceleration, mirror looking, gearshift, and static environment, shown in step 2.

The relevant keywords that were selected were determined as follows. The keyword sets of step 1 all included the words “driving” and “simulator” since this is the determined research topic. After having already determined two words of the set, a maximum of four or five keywords per set has been chosen as criteria. More than five would result in a too narrow-minded selection which is not the goal of this explorative literature research. The selection of the remaining two or three keywords that had to be chosen was based on selecting at least one keyword used for each driving test part description and at least one key word used to define its assessment criteria (Table 1).

The sets of keywords for the second step of the search plan were based on keywords found via the snowball effect (Dudovskiy, n.d.). The articles selected in the first step of the search plan were the input for defining new keywords to search for a new selection of potentially useful sources. These keywords were mostly found in the title or abstract of the selected articles in the first step.

The set of keywords resulted in a selection of articles. These articles were filtered via a title selection. Article titles that indicated research about driving simulator assessment of specific driving skills or driving performance, in general, were selected. After the title selection, there was an additional selection based on abstract information. When an article seemed usable based on its title, the researcher read the abstract to ensure that the title was not misleading about the research purpose of the article. The selected sources were read after the filtering process.

The second step of the search plan had the same structure as the first. However, the input of this step was determined by an adjusted set of keywords used for the research topic. After reading the first selection of sources, new information could be input for using additional or new keywords to find more articles. This process is also called the snowball effect (Dudovskiy, n.d.). An action, the “reading of selected sources,” causes other similar actions like: "reading more related sources to the research topic.”

The third step of the search plan included a third round of article research resulting from forward and backward searching. The sources of search steps one and two were read, and if considered valuable, there was a forward or backward search. In a forward search, sources are searched for that refer back to a specific article. On the other hand, a backward search aims to find references cited within a particular article (Briscoe et al., 2019). When the search for additional sources was finished, the search structure of the first two search steps was also used for the third search step.

The fourth and final search step contained summarizing and evaluating the information found in the selected articles of the previous search steps. As a result, an overview of what was known in the literature about driving simulator usage to measure and assess driving skills was presented.

The search for scientific articles had to be done using a literature database. Different kinds of literature databases can be used for article research. There is a general distinction between abstracting & indexing databases and publisher databases (Wijewickrema, 2021). A publisher database is limited to publications from a particular publisher. Since these sources are limited to publications from one specific publisher, they are unsuitable for a review. ScienceDirect (Elsevier), SpringerLink, and Wiley Online Library are examples of publisher databases. On the other hand, abstracting & indexing databases provide metadata and abstracts (Wijewickrema, 2021. Metadata includes the title and information about the author(s), publication date, journal title, volume and issue, keywords, DOI, etc. These databases could also be divided into discipline-specific or multidisciplinary sub-categories (Wijewickrema, 2021). The discipline-specific databases are selected very carefully based on multiple selection criteria. On the contrary, there are multidisciplinary databases that index academic journals from all disciplines. Examples of these interdisciplinary databases are Scopus and Web Science.

In addition to the main distinction between abstracting & indexing and publisher databases, there is Google Scholar. This database indexes websites with scholarly articles. Google Scholar does not disclose details on the web sides or journals that are indexed (Wijewickrema, 2021).

For this research, Scopus was used as a literature database. Scopus was considered as most suitable for this research because it is a multidisciplinary abstracting & indexing database. Since creating an overview of the information about driving simulator usage for driving tests is the goal of this literature research, an abstract & indexing database is preferred. Additionally, the search should include journals from all disciplines since, in this research, information from simulator usage in other disciplines could also benefit new insights. Thereby, Google scholar is not used for this research because of its disadvantage that it does not give any definition of scholarly, which could lead to results from predatory publishers or papers written by students. The choice between Web of Science and Scopus was based on the fact that Scopus is relatively more common and accepted (Burnham, 2006). A significant advantage of Scopus is that it allows forward and backward research (Burnham, 2006).

The semi-structured literature research on Scopus followed the steps of the search plan as described in this paragraph. The title and abstract selection in the first three search steps were based on eligibility criteria. Inclusion criteria were used when the articles matched the research goal of finding information about driving simulator usage to assess driving performance in terms of a driving test. Articles about driving simulations of motor vehicles on the road beside the car were included.

On the other hand, there were exclusion criteria. These criteria were used when articles seemed interesting based on the title selection but did have another research focus, as expected when reading the abstract. Multiple times, articles appeared interesting but were purely about automated vehicle (AV) applications. The other set of articles that had been excluded was related to investigating the problems of drug usage, insomnia, physical disabilities, and being able to drive in a car. Therefore, the exclusion criteria are determined during the literature research findings. The formulated criteria did exclude certain types of articles that were found multiple times during the research. It has also been found that findings from flight simulator usage and research were helpful. Table 5 below shows the literature research criteria.

Table 5

Set of eligibility criteria for literature research

Eligibility criteria for search results	
Inclusion criteria	• Simulated car driving • Simulated motor vehicle driving on roads (i.e., truck, motorbike) • Measurement of real-world driving (i.e., on-road drive, driving behavior, driving skills, assessment of performance) • Full article (not published abstract only)
Exclusion criteria	• The simulation used for AV application research • Simulators used for psychological and educational purposes • Physiological usage of driving simulators (i.e., drugs usage, insomnia, physical disabilities) • The driving simulation could not be related to driving assessment or to driving on the real road • Full text not available
Additional inclusion criteria applied in the review	• Development history of simulator technology (i.e., technological advancements, flight simulators)

Together with the search plan for the search structure, a framework was developed to structure the search for driving simulator usage to assess driving performance for a car-driving test. This framework structured the findings in the literature to create an overview in detail for each of the seven subdivided driving test parts in the Netherlands. Therefore, this framework is solely applicable to analyze the Dutch driving test. However, driving tests in other countries could also be investigated via this framework. A further explanation of the framework is in paragraph 3.2.1.

3.2.1 Development of the research framework

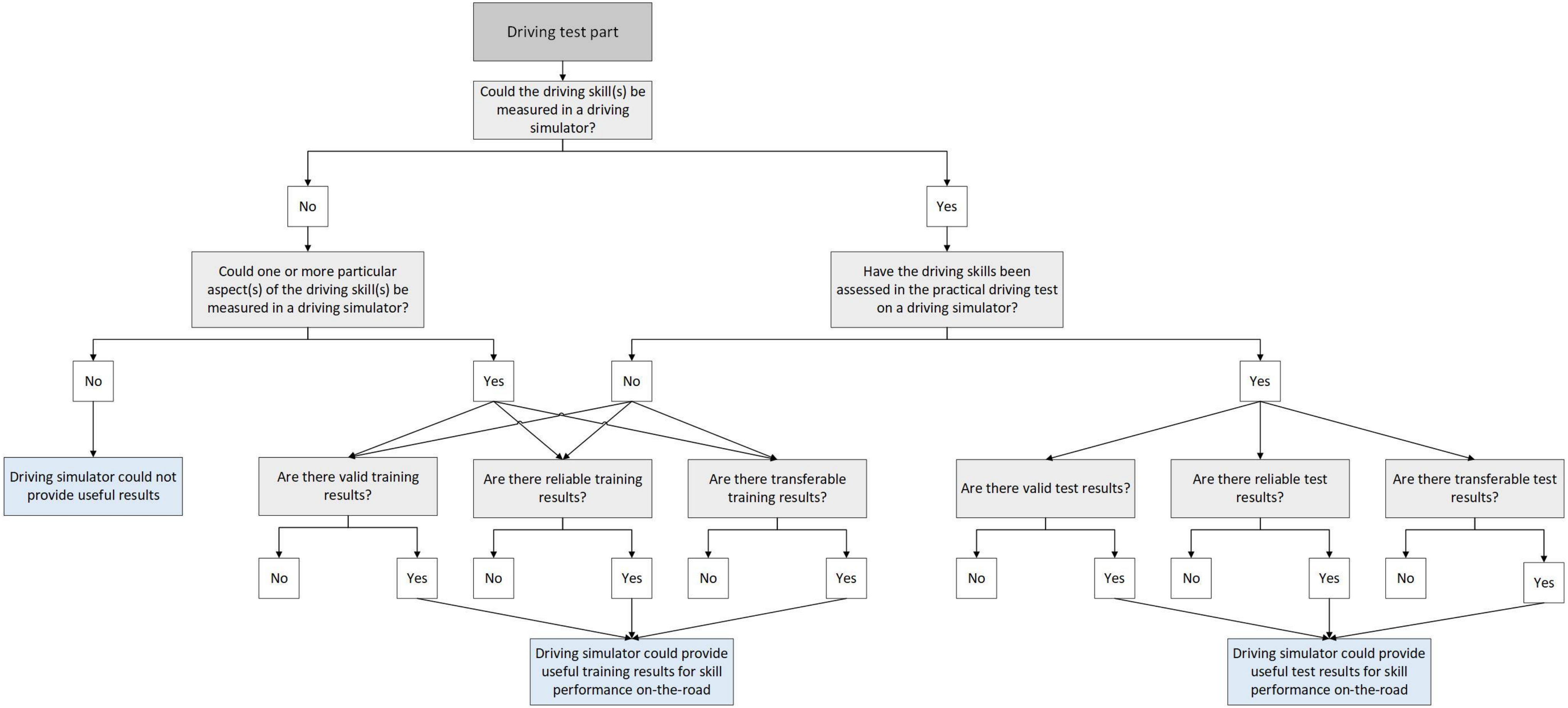

Figure 4

Research framework to investigate the opportunities for the driving simulator to be a suitable test tool that provides predictive results for driving performances on the road

Note. Own work

The self-conducted framework in Figure 4 structured the information of the literature research. The reasoning behind this framework is that it clarifies what information is available on driving simulator usage for a driving test and what information is missing. Therefore, the follow-up questionnaire and interview questions could specifically fill up these gaps in the framework when practical information is available.

There are seven parts representing the Dutch practical driving test for passenger cars. For each driving test part, the framework was filled in from top to bottom as far as possible with the information available from literature research. Additional practical information could fill in left over gaps in the framework. When no further information was available, the framework could not be filled in completely.

The framework is a yes/no decision tree. Each square in the decision tree represents a yes/no question. At the bottom of the decision tree are three ending squares representing the quality of the driving simulator results for a car-driving test. The validity, reliability, and transferability are explained in the previous paragraphs, 1.4 and 2.2.

Each part of the driving test represents a set of driving tasks defined by multiple driving skills, Table 3. The decision tree first asks whether or not all driving skills that have to be completed for one specific part of the practical driving test could be measured on a driving simulator. When the answer is “no,” the framework searches for the possibility that just one or a few driving skills could be measured instead. When the answer again is “no,” it means that none of the required driving skills for a particular part of the on-road driving test could be measured on a driving simulator, based on research findings in the literature. Therefore, the driving simulator should be considered “not feasible” for that part of the driving test. If the answer is “yes” for a few driving skills, information on the driving simulator's validity, reliability, and transferability are asked regarding training results. The reason to ask for driving simulator training results of different driving skills could provide interesting insights when no information is available on assessing a set of driving skills. These training results could show how specific driving skills could be measured on a driving simulator apart from their assessment (van Emmerik & Kappé, 2005). Therefore, this research follows the same reasoning as Kappé, de Penning, Marsman & Roelofs (n.d.): “driving tasks that can be trained well can also be assessed well.”

When the answer to the question on top of the decision tree is “yes,” it means that information is available on driving simulator usage to measure all driving skills required for the driving tasks of a particular part of the driving test. The decision tree's follow-up question is whether or not the driving skills have also been measured in actual driving testing circumstances. If there is any information available on testing these driving skills with the driving simulator, the bottom of the decision tree asks for information on driving simulator validity, reliability, and transferability.

The literature research aims to answer the bottom questions about the quality of driving simulator assessment results for the Dutch driving test. If these questions are unanswered after conducting the literature research, the follow-up questionnaire and interviews could provide additional practical information to fill these gaps. Therefore, the sequential structure of the research methods is essential.

3.3 Questionnaire

The output of the literature research served as input for the framework. Gaps that remained in the framework after conducting the literature research did indicate that information was missing. The questionnaire results were practical data on whether or not there was additional information available from practise to fill in these remaining gaps in literature or as complementary information to the statements already made in the literature.

The questionnaire period was between 30 June and 18 August 2022, with reminders, sent on 11 July and 29 July due to the issue that people could forget to answer due to the holiday period during these months.

The questionnaire aimed to use information from experts in driving training and licensing. Therefore, members of the *International Commission for Driver Testing* (CIECA) were chosen as respondents for the questionnaire. The international organization is active in road safety and driver testing (CIECA, 2022). Since the CIECA members represent specialized companies in driving training and licensing worldwide, the questionnaire was spread online via the CIECA database. There are 36 effective CIECA members. The questionnaire was sent to all of them (CIECA, 2022).

The list of questions sent to CIECA members starts with an opening statement. The explanation of the driving simulator’s validity, reliability, and transferability, as described in paragraph 1.4, was placed after the opening statement to ensure there could be no misunderstanding of these terms when the respondents filled in the questionnaire answers. The format of the opening statement, the explanation of the driving simulator's validity, reliability, and transferability, and the list of questions as it was sent to the CIECA members can be found in Appendix A.

The list of questions was conducted to discover whether other countries have any experience with driving simulator usage for driving test purposes. If it was the case that any research was done, a few questions were asked to get an overview of what aspects of the driving simulator were tested. At first, general questions were asked since the purpose was to discover which countries could probably share more information. The follow-up interviews contain more detailed questions specified for each country in particular.

The list of questions is written down in appendix B. All questions are yes/no questions with the possibility of adding an explanation. Question 1 generally asks whether or not any research has been conducted on driving simulator usage for cars or other vehicles. Question 2 is a more in-depth question as a follow-up to question 1, which asks whether or not the driving simulator research of the first question was related to driving skill performance measurement or other purposes. Sub-question 2a is about which driving skill(s) have been measured in the driving simulator if the answer was “yes” on question 2. Question 3 asks specifically for experiences with driving simulator usage for training purposes. Although this is not the main focus of the research, training and testing are aligned. If it is the case that a country does have multiple research findings on driving simulator training, this information could be relevant. Sub-questions 3a, 3b, and 3c are about the driving simulator validity, reliability, and transferability for training purposes. Question 4 asks explicitly for experiences with conducting a simulator driving test. If the answer to question 4 is “yes,” sub-questions 4a, 4b, and 4c ask specifically about the validity, reliability, and transferability of driving simulators for driving tests. Questions 5 and 6 ask whether or not the respondent would be open for a follow-up interview and if they want to fill in contact details. Question 7 allows one to write down any comments about specific questions or the research questionnaire.

3.4 Interviews

The output of the questionnaire was the input for the in-dept interviews. The questionnaire made it clear whether or not a CIECA member did have more information about research on driving simulator usage for driving tests. The selection of the members for follow-up interviews is presented in the next chapter.

The questions of interviews are open questions to get more detailed information. Based on the information in the questionnaire, the interview questions were formulated for each CIECA member in specific. The questions were prepared after the results of the questionnaire came in. Therefore, The explanation follows in chapter 5, which shows the questionnaire and interview results.

The results of the interviews were practical input for the framework and could fill in gaps that remained after the literature research. The results could also add information to framework parts on which the literature research already provided some information. After filling in the framework with the information from the interviews, an overview of the available information on each part of the Dutch driving test was created.

3.5 Example of framework application

The framework application is described in this paragraph using an example, which is used for each of the seven parts of the Dutch on-road car-driving test. The example is given for “ driving on straight and curved roads.”

The first question of the framework asks whether or not the set of driving skills required for this part of the driving test could be measured in a driving simulator. Table 3 shows the driving tasks which require particular driving skills performance for this part of the driving test. The definitions of the driving skills resulted in the first set of keywords used to search for sources in the literature research: Turn AND maneuvers AND driving AND simulator. The results of the first set of key words resulted in some information on the particular driving skills measured in a driving simulator. The search plan described in Figure 3 is followed to find more sources related to the framework's different parts. For this part of the driving test, using the snowballing effect did not lead to other key words that provided new relevant sources. On the other hand, using the backward and forward search did lead to a few new sources. Eleven relevant sources were gathered for this part of the driving test.

The search for the specific results found in the literature research was based on the questions in the framework. The results showed information on the set of driving skills as described in Table 3. Information on speed control, gaze behavior, and lane-keeping performance was found. The available information will be explained in the following chapter, paragraph 4.2. Since the information was available on measuring the set of driving skills, the next question of the framework was: " have the driving skills been assessed in the practical driving test on a driving simulator?" The research of Gemonet et al. (2021) did show results for a 40-minute driving test on the same circuit for both the simulated and real environment. Results are further described in paragraph 4.2 as well. Since the sources showed results on testing the required driving skills in a driving simulator, the questions on the lowest level of the framework are: "Are the test results transferable, reliable, and, or valid?" Information was found for all three factors. The results are further described in paragraphs 4.8.1 until 4.8.3.

For " driving on curved and straight roads," information gaps could be filled in on the relevant parts of the framework. However, there was a small number of sources found. Therefore, additional information from practice was searched. Results from Finland and Sweden show that training on how to drive on curved and straight roads could be done in a driving simulator in these countries. Sweden provided additional information on hazard perception while driving in the simulator. No further information was found for this part of the driving test. All information found for this part of the driving test is shown in paragraph 4.9.

4. Results literature research

This chapter shows the literature research results per each of the seven driving test parts. The relevant sources for each driving test part are presented in Tables 6 to 12. Each table shows relevant sources regarding driving simulator usage and the usefulness of its driving performance results. Paragraphs 4.1 until 4.7 of this chapter elaborate on the literature research results. The following words used for source descriptions are highlighted in bold and italic text: training, assessment, transferability, reliability, and validity. To show which results are directly relatable to questions from the framework. As a follow-up on the highlighted results, paragraph 4.8 elaborates more on the usefulness of driving simulator results regarding transferability, reliability, and validity. The final paragraph, 4.9, fills in the framework for each part of the driving test based on information from the literature research.

4.1 The start of the driving test

The start of the driving test has multiple elements that could be researched. The start of the driving test was not measured in the literature. Therefore different sub-elements were investigated during the literature research instead. Results were found by using keywords that represented these different elements separately. The various considered aspects during the literature research were, on the one hand, the clutch, gearshift, and accelerator usage, meaning the car handling skills. On the other hand, mirror looking and speed variability are considered significant elements of the vehicle launch when starting with the driving test.

Findings on particular driving skills performance related to the start of the driving test are described in the research of Klüver et al. (2016) and van der Meulen, Kun & Janssen (2016). The study of Mayhew et al. (2010) did investigate the validity of the driving simulator when assessing driving performance and skills. This research is not focused on the start of the driving test. However, this source is considered important here since it relates the driving performance measurement of specific driving skills required during the start of the driving test to the usefulness of the assessment results. The research of Wang et al. (2010) searched, in particular, the task performance of destination entry time on a navigation device in a car which is one of the starting actions during the drive-off in a driving test.

Table 6

Literature research results: Start driving test

Source	Research purpose	Main conclusions
Zhao & Sarasua, (2018)	Ensure validity of driving simulators based on visual limits of humans, their perceptions, and raster characteristics	• Insufficient display resolution can decrease the ***validity of the driving simulator results*** because of degradation in the visual fidelity of the simulator • Improve display resolution does not significantly affect speed choice and ***lane position validity***. • Widening the field of view does affect the ***validity of speed choice and lane positioning***
van der Meulen, Kun & Janssen, (2016)	Finding if there is a difference in behavior when starting driving after parking and taking over from the autonomous driving car	• The simulator driving scenario's made clear that there was no difference in driving performance and gaze behavior related to distraction in both situations • The driving simulator is capable of measuring and ***assessing*** driving performance in this research
Wang et al. (2010)	The study investigates whether or not there is a significant difference between destination entry task duration* performance in the simulated versus the on-road environment	• To be able to ***assess primary task performance***, fixed base driving simulation is recommended • The results show a significant slightly greater distinction between different navigation devices on-road than in simulation, which means a longer task duration time on-road
Mayhew et al. (2011)	The study wants to investigate the validity of the driving simulator for measuring driving performance or skill	• The advantage of computer scoring by the driving simulator is that it objectively measures driving skills, while in the case of driving examiner measurement, there could be bias • Examiner scoring could offer performance categories like hazard anticipation, which computer assessment could not • A combination of both computer assessment and examiner assessment is suggested as the best alternative to ***assess driving performance*** • The findings of this research suggest that the driving simulator could be used as a substitute for driving performance as measured in the on-road test • Simulators must be validated before they are used for a ***driving assessment***
Klüver et al., (2016)	Investigating the difference in performing secondary driving tasks between fixed-based "in-car" set-up with full-scale mock-up and "out-of-car" set-up with only full-scale dashboard	• Speed variability is significantly lower in "out-car" set-up • Glance in rear mirrors significantly higher "in-car" set-up

* Entry task duration is the time from a subject's input of the first character of an address until the entry of the last character (Wang et al., 2010)

4.2 Driving on straight and curvy roads

The literature research for this part of the driving test focused on a search for measuring and assessing the performance of driving skills needed while driving on curved and straight road sections in and outside the built-up area.

Driving on curved and straight roads results in a significant distinction in terms of required driving skills and driving behavior. The different roadway geometry does affect perceptual cues to accomplish curve and straight driving negotiating (Shinar, 2016). Drivers on curved roads must rely on different signals for directional control than straight-road drivers (Shinar, 2016). Therefore, when driving on these different road types, there are multiple factors to account for that should be assessed in a driving simulator.

Results of the literature research show various factors that play a significant role. There were a few sources (Klüver et al., (2016); Sahami & Sayed, (2013); Ronen & Yair, (2013)) found that investigated the driving simulator validity for driving on straight and curved roads in terms of adaptation to the driving simulator instead of driving on the real road. Other sources investigated whether or not there was a difference between gaze behavior on the driving simulator and the real road for driving performance on straight and curved roads (Wang et al., (2010); Robbins, Allen & Chapman, (2019); Feng et al., (2020)). Gaze behavior is essential for driving on straight and curved roads. Research into other driving skills that determine the driving performance for driving on straight and curved roads in a simulator can be found in several sources. Lane-keeping performance and speed control differences between a simulated and real road environment were investigated by: Blana & Golias (2002), Erséus, Trigell & Drigge (2015), Schiro et al. (2014) and Kaptein, Theeuwes & van der Horst (1996). The performance of these driving skills was researched under driving test conditions. Gemonet et al. (2021) researched whether or not the driving simulator behavior matches the behavior on the real road during a 40-minute driving test on the same circuit in both environments. Rapid changes in the driving environment captured with the eye and the body feeling of moving while driving on straight and curved roads relate to a problem that could exist in a driving simulator, namely simulator sickness. It is a type of motion sickness expressed in nausea (SWOV, 2010). Suppose a person is driving in a simulator without moving base. In that case, there is a risk of motion sickness. There is a lack of feeling that your body should move during interaction with the environment. However, it is essential to know from experience that drivers with little or no driving experience are less sensitive to simulator sickness (SWOV, 2010).

Table 7
Literature research results: Driving on straight and curved roads

Reference	Research purpose	Main conclusions
Klüver et al., (2016)	Determine the validity of the different types of driving simulators	• The horizontal field of view in a simulator positively correlates with driving performance in terms of speed choice and lateral position
Sahami & Sayed, (2013	Investigating what factors could influence the adaptation of a driving simulator to increase its validity	• In fixed-based driving simulators, there is no feeling of acceleration (longitudinal and lateral), and therefore no feedback is present to correct the speed, especially during driving corners; there is a lack of speed correction • A driving scenario should not focus on a particular aspect of driving only; it can cause unwanted bias • Driving simulator adaption is strongly task-depended • A driving simulator scenario on a simple and straight road segment with a constant speed seems improper to use if ***valid results*** are aimed for
Wang et al. (2010)	Investigating whether or not glance frequency and duration do differ significantly between the on-road and simulated environment*	• Eye-tracking measurement is more difficult to capture on-road • The number of glances is underestimated by simulation; however, this effect is not significant • A highly significant main impact is found for a device on glance duration • ***Relative validity*** for the total glance duration is found • When a touch screen is used in a driving simulator, a slight underestimation of glance duration is found, which indicates ***absolute and relative validity*** for rank-ordering devices
	Investigating whether or not the percentage of time that eyes were focussed on the road, during intervals of 30 seconds, differs between the on-road and simulated environment	• Both ***relative and absolute validity of driving simulator usage*** applies for this measure when compared to the on-road • There is a slightly greater urgency to complete the secondary tasks under real-world conditions, where the risks of distraction are objectively greater
	Investigating whether or not the total number of single glances with a duration longer than 1,6s (long time of off-road distraction) differs between the on-road and simulated environment	• ***Relative validity*** was found for the number of long off-road glances between the two environments
	Investigating whether or not the longitudinal control in terms of mean speed differs between on-road and simulated driving	• ***Relative validity*** was found when comparing the driving simulator usage and on-road driving in general; no distinction between different types of vehicle or simulator devices should be made here • ***Relative validity*** can also be found for the standard deviation of forward velocity between the two environments

Gemonet et al., (2021)	Investigate whether or not the driver's behavior in a simulator matches the real behavior on the road during a 40 min driving test on the same circuit in de simulator as on the road	• The driving behavior adaption in a simulator depends on the type of road involved (straight, curved, or urban roads) • There is a need to distinguish between driving performance on straight and curved roads • Simulator sickness could arise in simulators, which influences the driving performance • Drivers drove faster on the straight lines during the test on the simulator compared to the real road • Drivers tend to show better compliance with speed limits on a simulator than in the real world • For straight road types, speed variability in a driving simulator is more significant than on the real road due to the mental workload • For both road types, drivers brake later while driving on a simulator compared to driving on the real road • There is a driver's misperception of curvature radii in a simulator which influences the moment of braking during curve negotiation • For straight roads, it is essential to have vibration feedback and the sound of the engine that influence the braking force • The final results show a promising match between the driving simulator and real road for driving performance on both road types
Blana & Golias, (2002)	Investigate the differences related to lateral displacement for both straight and curved driving between the driving simulator and real road	• The mean lateral vehicle displacement is higher in the real world than in the simulator • The difference between lateral vehicle displacement decreases when: the higher speed at curved roads or lower speed at straight sections • The standard deviation of lateral displacement is higher in the simulator for both curved and straight roads than on the real road • Higher speeds on curved roads indicate that the feeling of safety in a simulator decreases faster than on the real road • For speeds below 70km/h, drivers perceive the same feeling of risk in a simulator and on the real road related to unexpected occurrences at the edge of the road • In a driving, simulator drivers seem to underestimate the risk for both curved and straight roads • On straight road sections, real road drivers position their car closer to the center of the road compared to simulator drivers • Cues adopted by drivers on the real road for distance perception are misused in the driving simulator
Robbins, Allen & Chapman (2019)	Investigate whether or not the driving behavior at intersections in a simulator is similar to the real road	• The difficulty of the driving task is significant for the driver's visual search strategy adaption • In general, drivers are looking for more potential danger when they are making a right turn (in the situation of driving on the left side of the road, UK study) compared to a left turn and straight driving • The driver's mean fixation duration is longer in the simulator than in real situations compared to curved driving • Complex maneuvers, like right-turn driving, do reduce the difference in the mean fixation duration between driving in the simulator and on the road** • The demand of the driving task needs to be at least moderate for all visual attention measures to be comparable between the simulator (high fidelity in this research) and the real road

Erséus, Trigell & Drigge (2015)	Evaluate the relationship between the driving skill to the measurements done performing primary driving tasks, i.e., driving on a real straight road	• The research shows that drivers with high path-tracking skills are closer to steady driving in constant-radius road curves • Curves require accurate input from the driver
Feng et al. (2020)	A driving simulator is used in this study to measure the pupil diameter as one of the most essential assessing indicators of the driver's mental workload	• There is a positive relationship between pupil diameter and the driving speed • The driver is more focused on the road when driving at a higher speed, and therefore the pupil diameter is larger • The driving simulator is successfully used in this research as a tool together with an eye tracker to investigate the influence of various speeds in curved and straight driving on the pupil diameter
Ronen & Yair, (2013)	This research tries to get more insight into the differences in adaptation period for driving on different roads in a simulator	• The curved road is relatively more demanding and therefore requires longer adaptation times compared to straight roads • Need for improvement of more performance measures in a driving simulator for curvy roads • Roads with different characteristics and demands may require other time to achieve simulator adaptation
Kaptein, Theeuwes & van der Horst (1996)	The research investigates assessing driving behavior in the simulator in terms of validity	• There are limitations to ***assessing driving behavior*** in a mid-level fixed-base driving simulator • The results for behavioral variables are ***relatively valid***, which means ***no absolute validity*** for driving speed choice and lane-keeping performance could be achieved • For route choice decisions, ***absolute validity*** is found, and therefore drivers show the same behavior as on the real road
Schiro et al., (2014)	The research focuses on investigating the steering wheel positioning during driving on straight and curved roads	• Greater accuracy was shown in the car than in the simulator for lane-keeping performance • A more significant variance was shown in the simulator compared to the real road for both the driver's input to the vehicle (steering wheel positioning) and output (lane positioning)

* Glance frequency and duration is referred to as the glancing at the display and input devices during destination input entry; in other words, the level of distraction caused by a secondary task while driving on a straight road (Wang et al., 2010)

** Mean fixation duration is how long drivers pay attention to an individual part of the visual scene

4.3 Driving near and around intersections

Intersections are hinge points for the road network and link two or more roads to each other (Huang et al., 2021). Therefore driving around intersections does include some important factors that determine the environment in which a driver should act. The most critical factors for assessing driving at intersections are the ego vehicle, a preceding vehicle, an oncoming vehicle, and other road users that cross the intersection (Kusakari et al., 2021). Given these factors, the simulation of intersection situations on a driving simulator should also include them to be comparable to the real road. Additionally, multiple design options exist for intersections, like single or double driving lanes and many driving actions (Brusque, 2008). Entering an intersection, the driver can choose to go in multiple driving directions. The intersection can be signaled with traffic signs or not, resulting in different driving conditions (Pawar & Velaga, 2021). Another factor influencing the driving conditions around intersections is time pressure due to other vehicles (Pawar & Velaga, 2021). All these environmental factors and the intersection design result in complex driving situations to assess on the road.

The driving simulator must replicate the traffic conditions on the real road closely for a comprehensive assessment (Eden, Tanguiam & Palmiano, 2021). Therefore, the following studies did research whether or not visual attention and driving behavior around intersections in simulated environments did differ from the real road situations: Robbins, Allen & Chapman (2018); Robbins, Allen & Chapman (2019); De Winter, De Groot, Spek & Wieringa, (2009); and González-Ortega et al., (2018). These research studies concluded that only high-fidelity simulators could validly represent the complex intersection situations of real roads. The research of Zöller, Abendroth & Bruder (2019) did dive deeper into the braking behavior when driving at intersections in a simulator. It concluded that braking initiation, average velocity, and gap acceptance are complex factors to capture in a driving simulator. Therefore, a low-fidelity driving simulator would not be suitable, they concluded. Thereby, the research of Montella et al. (2010) found that simulator sickness plays a significant role besides the importance of the high-fidelity level of simulators.

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Table 8

Literature research results: Driving near and around intersections

Reference	Research purpose	Main conclusions
González-Ortega et al., (2018)	Analyse driving efficiency using different driving simulator scenarios in which the driving performance of drivers can be tested	• For different crossroads, the simulator was ranked positively regarding driving interaction and the usefulness of driving learning in a simulator. • Similarity to the real world
De Winter, De Groot, Spek & Wieringa, (2009)	The driving simulator is used to investigate the acceptance of the gap between two successive vehicles concerning the driving skills and driving style	• left turn at an intersection is one of the most dangerous driving tasks • Whether a distance gap is safe between two consecutive vehicles depends on the time between them • Left turn acceptance in a driving simulator correlates with driving skill and driving style (violations) • The results of this study are partially generalizable to the roads
Zöller, Abendroth & Bruder (2019)	The research aims to investigate the driving simulator validity for braking behavior at intersections	• The braking behavior near urban intersections differs between simulators and real road • The average velocity is significantly higher when approaching an intersection in a simulator compared to the real road • There are significant differences between the simulator and the real road in terms of the timing of braking initiation • The driver brakes significantly later in the driving simulator compared to the real road • Drivers do brake more intensively in simulators than on the real road • Factors that influence the braking initiation are the turning direction, horizontal viewing angle, and motion simulation • A low-fidelity simulator is not suitable for reproducing ***valid braking behavior***
Robbins, Allen & Chapman (2018)	The research investigates the gap acceptance behavior around intersections while approaching both motorcyclists and cars	• There is an inappropriate gap selection at intersections in front of motorcyclists compared to cars • The greater gap acceptance for approaching motorcyclists is also found in high-fidelity simulators, not in medium-fidelity simulators • Driver's behavior at intersections needs to be investigated in a realistic simulator environment to generalize the behavior to real road driving
Robbins, Allen & Chapman (2019)	The study investigates whether or not the visual attention of drivers at intersections in the driving simulator is similar to the real road	• There is evidence that a high-fidelity simulator is ***valid*** regarding the visual attention of drivers at intersections
Montella et al., (2011)	The study investigates the driving behavior around rural intersections in terms of speed, deceleration, and lateral position using a driving simulator	• The lateral position around intersections on the road is easily measured in simulators compared to the real road for which accurate sensors are needed • The use of a driving simulator for investigating driving behavior at intersections does have shortcomings: simulator sickness, ***validity***, and level of realism compared to the real road

4.4 Merge & exit on the highway

Merging (or exiting) on the highway is a complex task that requires consensus with other cars. The driving behavior during merging on the highway could be measured in a driving simulator (Okuda et al., (2021). However, this study shows the interaction under controlled environmental factors, which shows the complexity of the driving task. The study of Calvi, Benedetto & Blasiis (2012) showed this complexity by verifying local differences in driving speeds while measuring the driving performance in a simulator compared to designed speed limits on exit lanes. The study of Yamada, Matsuyama & Uchida (2014) confirms the complexity of the driving task. The study argued that the predefined driving scenarios in a simulator could not capture other vehicles not defined in the design like reality can in terms of unforeseen environmental factors. A possible side effect that increases the difficulty in simulating this driving task is the possibility of simulator sickness (Bernadin et al., 2018).

Table 9

Literature research results: Merge & exit on the highway

Reference	Research purpose	Main conclusions
Calvi, Benedetto & Blasiis, (2012)	This research used a driving simulator to study the driving performance while driving towards a divergence area on the highway and decelerating during an exit maneuver	• The driving simulator was able to provide significant information about the driving performance of deceleration lanes • When approaching the exit lane, the driving performance is highly variable depending on the main traffic flow • The speeds at the end of the exit lane did not seem to depend on the main traffic flow • The local speeds of vehicles approaching the end of the diverging lane, the highway exit, are higher in the driving simulator scenarios than the designed speeds
Okuda et al. (2021)	The research investigated the decision-making process of drivers on whether or not they accept a merging car at the main highway lane	• The study used a driving simulator to measure the acceptance of a car coming from a merging lane • In this study, the driving simulator was able to verify the process of decision-making with other cars while focussing on a conflicting scenario during the merging task with controlled factors
Yamada, Matsuyama & Uchida, (2014)	The study tries to analyze the interaction between two vehicles in neighboring driving lanes while one driver is cutting the other in front of the merge	• The study used automatic controls for two interacting vehicles based on a predefined scenario which showed results for their interaction behavior • The study also mentioned that in the real world, there are other vehicles involved during the interaction, not only the ones of the predefined scenario
Bernadin et al., (2018)	The study investigated the eye and head movement behavior of a driver performing a lane merging task on the highway during multi-tasking using a driving simulator	• Simulator sickness seemed to be a possible side effect • The nature of the individual driver plays an important role; therefore, there were differences for specific drivers • In general, the glance frequency of drivers during pre-merge and merge activity did increase

4.5 Overtaking and side-way movements

One of the leading causes of car accidents on rural roads is overtaking, which involves the risk of head-on collisions with oncoming traffic or rear-end collisions between successive vehicles (Branzi et al., 2021). Therefore, an essential part of car driving is following preceding cars and overtaking them at the right time (Bergeron et al., 2006). To change lanes safely, the driver should estimate his relative position on the road regarding speed and distance to other vehicles (Bergeron et al., 2006). To change lanes and overtake preceding vehicles, two essential indicators should be assessed regarding driving performance, namely turning on the turn signal and glancing in the outside mirrors (Brusque, 2008).

Estimating one's relative position on the road compared to other vehicles is especially hard for novice drivers (Bergeron et al., 2006). Yang, Jaeger & Mourant (2006) research compared the driving behavior of novice and experienced drivers regarding lane change maneuvers. It concluded that using driving simulators would be helpful for these novice drivers to acquire the skills necessary for these maneuvers. The research of Wang et al. (2010) and Pawar, Nagendra & Velaga (2021) present the relative lane positioning of cars in simulator experiments compared to the real road. Regardless of differences found in the lane change maneuver performance, most drivers reported that they did not feel any difference concerning the feeling of driving in a simulator compared to driving on the road regarding the lane change maneuver (Pan & Shen, 2022). A few reported simulator sickness (Pan & Shen, 2022).

Table 10

Literature research results: Overtaking and side-way movements

Reference	Research purpose	Main conclusions
Wang et al. (2010)	Investigating whether or not the lateral control, the standard deviation of lane positioning differs between the on-road and simulated environment	• A significant effect was found for the standard deviation of lane positioning; the standard deviation was higher for the simulator than for on-road • ***Relative validity*** was found for the comparison between the two different environments
Yang, Jaeger & Mourant, (2006)	The research does investigate the driving behavior of both a group of novice and experienced drivers while they are performing lane change maneuvers using a fixed-base driving simulator	• The driving simulator may be helpful for novice drivers to acquire skills that are necessary for safe lane change maneuvers • A few significant skills are required simultaneously to perform lane change maneuvers • These fundamental skills include: controlling the speed and direction of the vehicle and scanning the surroundings of the car in the rear- and side-view mirrors at appropriate times • The driving simulator of this study did not duplicate a blind spot; more driving simulators do not have this blind spot • Having a blind spot is essential when performing a left lane change maneuver • Most driving simulators do have both a front and rear view; having a blind spot includes a side view as well
Pawar, Nagendra & Velaga, (2021)	The study examines driving performance related to overtaking maneuvers and crash probability during increased time pressure conditions	• A fixed-base driving simulator was used to examine the driving performance, and it provided continuous data on longitudinal and lateral speed, acceleration, and lane position • The driving simulator measured that drivers are more leaning towards risky decisions for overtaking when the time pressure increases to complete the driving task
Pan & Shen, (2022)	A driving simulator experiment was conducted to assess the driving risk of novice drivers during the overtaking maneuver on two-lane highways	• A small number of participants (2) did report that they suffered from simulator sickness • The other participants reported that they did not feel any difference between driving in the driving simulator and driving on the real road • The results of the study could be a bit biased since the simulator experiment could diverge from real driving conditions

4.6 Special road sections

There are different special road intersections. These intersections can be linked to “special” traffic situations that include crossings with varying types of vehicles apart from the car (R.V.S.S., 2019). The most common intersections in this category are defined for this research: pedestrian, railroad, and bicycle crossings. These special road intersections have the same complexity as the regular intersections, apart from the fact that different types of road users are involved. This type of intersection is assessed separately from the other intersections during the Dutch driving test. However, the sources found in the literature do not discuss the assessment of driving skills required for the driving tasks related to driving at these intersections. The results in the literature show that the driving simulator is used for different research purposes related to improving safety around these intersections. These sources indicate that the driving simulator can measure driving behavior performance at these intersections. Larue, Blackman & Freeman (2018) and Landry et al. (2018) investigated railway crossing driving behavior. Both studies used a driving simulator for that. The driving simulator measurement of driving behavior and its resulting safety around pedestrian crossings is discussed by Parkin et al. (2022), Dozza et al. (2020), and Sadraei et al. (2020).

Table 11

Literature research results: Special road sections

Reference	Research purpose	Main conclusions
Landry et al. (2018)	Driving behavior at highway-rail crossings has been studied in real-world crossing scenarios using a driving simulator	• The driving simulator was able to simulate representative crossings • The data from this research suggest that driving simulator participants do understand what they have to do in terms of safety around passive crossings (which have no warning devices) but not around active crossings • *The study could not provide a ***valid representation of real-world driving behavior around railroad cross-sections***
Parkin et al. (2022)	The study used a driving simulator to test trust in AV for cyclists and pedestrians involved with different priority-based maneuvers like passing a pedestrian crossing	• Between the road user types, there was no difference in trust • Between the real road and simulated environment, there were differences in trust however • These differences depended on the complexity of the maneuver • The study suggests a need for caution in reliance on simulator-only experiments regarding priority-based maneuvers
Dozza et al. (2020)	The research investigated the driver's response process when negotiating an intersection with a pedestrian using a fixed-base driving simulator	• Visibility of the pedestrian presence around the pedestrian crossing and pedestrian time to arrival are the two most important factors for driving behavior • It is not known from the results whether or not inexperienced drivers do behave more realistically in a driving simulator than experienced drivers
Sadraei et al., (2020)	The study used a driving simulator to evaluate the interactions between pedestrians, humans, and automated vehicles in crossing situations	• The results of the study show that measuring braking behavior (acceleration, speed, and distance to pedestrians) around crossings with pedestrians in the simulations is a safe and ***reliable method*** for these interactions
Larue, Blackman & Freeman (2018)	The study used a driving simulator to measure railway-level crossing rule violations objectively	• The results show that increased waiting time increased the likelihood of risky behavior • The risky behavior was successfully measured in different scenarios developed in an advanced driving simulator

4.7 Special road maneuvers

As described by the CBR (n.d.-a), the special maneuvers are reversed driving, making a reversed turn, turning by reverse driving, turning by making half a turn, hill start, and parallel parking. These maneuvers are usually performed in a more static traffic environment than the other driving test parts. Therefore, car handling is essential to simulate. Pawar, Velaga & Sharmila's (2022) study concluded that fixed-base driving simulator elements like the gearbox, braking system, and accelerator system are rated as very realistic compared to the real vehicle steering elements in a car. However, not only car handling skills are essential for special road maneuvers, but high-order skills are also required. These high-order skills are essential for every driving task. Taspi, Vissers & Buuron (2022) concluded that the driving simulator could be a valid tool to assess them. The studies of Ohama et al. (2008) and Yukawa, Sonoda & Wada (2020) showed that the driving simulator could be a valuable research tool to measure the reversed parking driving task as one of the special maneuvers. Research on using a driving simulator for other special road maneuvers was not found.

Table 12
Literature research results: Special road maneuvers

Reference	Research purpose	Main conclusions
Tsapi, Vissers & Buuron, (2022)	Explorative research to investigate the opportunities to train, test and assess high-order driving skills to improve safety on the roads	• The driving simulator seems to be a ***valid tool*** for measuring high-order skills compared to the current practical driving test • There are already simulator training programs that improve the high-order skills • There is evidence that training high-order skills do improve safety on the road
Ohama et al. (2021)	The research is focused on improving reversed perpendicular parking by testing different scenario's in a controlled environment on a display-based driving simulator	• Parking is a driving task that most drivers think that they are not as skilled as they want to be • The start position is the most crucial aspect of reversed perpendicular parking • Simulator results indicated that instructions in the simulator might change the reversing position
Yukawa, Sonoda & Wada, (2020)	The research focussed on driving simulator tests for steering timing as a possible factor for reversed parking skill improvement	• A feasible parking space is determined by the start position of turning • Despite the development of vehicle technology, manual driving is and will be present for the foreseeable future • Even though there are possibilities for driving simulator technologies, driving performance improvement on reversed parking remains relevant because of implementation challenges
Pawar, Velaga & Sharmila (2022)	The research focussed on comparing driving behavior measures in the real world and the simulations to assess the validity of the driving simulator; a fixed-base driving simulator is used to test 30 experienced male drivers	• The sense of realism in the gearbox of a driving simulator is 66,7%; this percentage of participants rated the simulator as very realistic • The sense of realism of the accelerator and braking system in a driving simulator is both 60%; this percentage of participants rated the simulator as very realistic • The simulator of this study can be used as a ***valid research tool*** to investigate the influence of driving conditions on the change in driving behavior

4.8 The literature research results on transferability, reliability, and validity

The results of the literature research show whether or not the information is available about driving simulator usage to assess predefined driving tasks of the practical driving test. The assessment of the driving tasks could be found via information about measuring driving skills that are part of the driving task in the practical driving test. The literature research results are structured in transferability, reliability, and validity to determine if the driving simulator results could be used in a driving test context in the future.

The results show that relatively more detailed literature is found on driving simulator usage for driving on straight and curvy roads compared to the other six elements of the driving test. However, finding information about driving simulator usage to assess required driving tasks for special road maneuvers and driving on special road intersections seemed relatively challenging. Thereby, the type of information that is found per driving test element significantly differs. Therefore, for each of the seven driving test elements, the results are subdivided based on the information on the transferability, reliability, and validity of driving simulator usage.

There were some sources not directly related to information on these three factors. However, these sources clarified that the driving simulator could measure driving tasks, not to assess driving performance but for other purposes like safety. These sources show the societal importance of research into using driving simulators to measure driving tasks. Therefore, the information from these sources could provide insights for indications about driving simulator usage to assess driving performance in the future.

4.8.1 Transferable driving simulator results

Start driving test

Research by van der Meulen, Kun & Janssen (2016) showed no difference between the driving simulator and real road regarding gaze behavior and driving performance due to distractions in the predefined scenarios. Gaze behavior and driving performance during the start of the car after parking were the same in multiple defined scenarios, which means that the driving simulator results were transferable.

Straight and curvy roads

Concerning the field of view for both types of roads, the speed choice and lateral position on roads simulated in the driving simulator depend on the horizontal field of view, which also holds for driving on real roads (Klüver et al., 2016).

Regarding speed correction, the lack of feeling of acceleration (longitudinal and lateral) in a fixed-base driving simulator results in no feedback to correct the speed, especially on corners of curvy roads. Therefore, this type of simulator seems unsuitable for simulating driving on curvy (and straight) roads to produce transferable results for speed correction and lateral position (Sahami & Sayed, 2013). Furthermore, other differences exist between driving performance in a simulator and on the real road that negatively influences the transferability of the simulator results. Gemonet et al. (2021) mention the following differences:

- Drivers drive faster on straight lines in a simulator
- Drivers tend to show better compliance with speed limits on a simulator
- The speed variability of a simulator on straight roads is more significant than on the real road due to the workload
- The braking behavior in a driving simulator is later for both road types compared to the real road
- The misperception of curvature radii in a simulator influences the moment of braking during curve negotiation
- Vibration feedback and the sound of an engine on straight roads is important and influences the braking force in a simulator and on the road

Additional arguments for and against the use of transferable driving simulator results are given by Blana & Golias (2002) in terms of vehicle lateral displacement and safety. The mean vehicle lateral displacement is generally higher in the real world than in the simulator, indicating that the simulator results are not transferable. However, the mean value for vehicle displacement is not entirely representative regarding driving performance. Particular moments are better representatives of the driving performance at any time since that could provide us with more accurate information. Therefore, Blana & Golias (2002) concluded that the lateral vehicle displacement decreases in a driving simulator when the speeds at curved roads are higher and at straight roads are lower, resulting in greater compliance between the on-road and simulator results for curved roads. However, another difference between the driving simulator and on-road results can be found in the car's position at the center of the road. Real road drivers position their cars closer to the center than simulator drivers. On the other hand, drivers underestimate the risk of driving on straight and curved roads in a driving simulator. However, the feeling of risk in a driving simulator differs under some circumstances from the road. Drivers perceive the same risk for driving speeds below 70 km/h. However, the feeling of safety at higher speeds on curved roads increases faster in a simulator than on the road. Thereby, Blana & Golias (2002) did prove that the distance perception of drivers in a driving simulator is not similar to on-road driving.

The research of Robbins, Allen & Chapman (2019) did discover that the driving task needs to be at least moderate for all visual attention measures to be comparable between a high-fidelity simulator and the real road.

Adaptation time to the driving simulator also plays an essential role in the transferability of the driving performance results (Ronen & Yair, 2013). Roads with different characteristics may require other adaptation times for the driving simulator. For example, curved roads are more demanding and require longer adaptation times for the driving simulator than straight roads (Ronen & Yair, 2013). Therefore, attaining transferable driving simulator results for simulating curved roads could be more challenging than straight roads.

Driving near and around intersections

González-Ortega et al. (2018) did use different driving simulator scenarios in which the driving performance of drivers could be tested. One of the research conclusions was a positive ranking for the driving simulator regarding driving interaction at crossroads in particular.

De Winter et al. (2009) did use the driving simulator to investigate the gap acceptance between two successive vehicles concerning driving skills and style. The driving simulator was used as a research tool, making it possible to conclude that the complex left turn acceptance at an intersection correlates with driving skill and style. Finally, de Winter et al. (2099) did conclude that the simulator results were partially generalizable to the real roads.

The research of Zöller, Abendroth & Bruder (2019) did investigate another important phenomenon around intersections: braking behavior. Essential factors of the driving simulator that seemed to influence the braking behavior were determined as the turning direction, horizontal viewing angle, and motion simulation. Zöller, Abendroth & Bruder (2019) concluded that the braking behavior near urban intersections differed between simulators and the real road, making the simulator results not transferable. Significant differences in the driving behavior were found in a significantly later timing of braking initiation in the driving simulator and more intensive braking in the simulator. The research did find out that as a cause for the intensive braking behavior, the average velocity was significantly higher when approaching an intersection in a driving simulator compared to the real road.

Merge & exit on the highway

Sources found were based on using the driving simulator as a research tool for other research purposes than investigating whether or not the driving simulator could be used for driving to provide transferable driving performance results.

The research of Calvi, Benedetto & Blasüs (2012) used the driving simulator to study the driving performance towards a divergence area on the highway and deceleration during an exit maneuver. One of the research conclusions was that the driving simulator provided important information about the driving performance on deceleration lanes. The information from the measurements in the driving simulator could be transferred to real road driving.

Okuda et al. (2021) also used the driving simulator as a research tool. The research investigated the decision-making process of drivers on whether or not to accept a merging car in the main highway lane.

According to this research, the driving simulator verified the decision-making process with other cars during the merging task on the highway under controlled circumstances in a conflicting scenario. On the other hand, the research results of Yamada, Matsuyama & Uchida (2014) clearly showed that other vehicles are involved during the interaction and not only in the predefined scenario of a driving simulator. The research analyzed the interaction between two vehicles on neighboring highway driving lanes while one driver cut the other in front of the merge. The research concluded that the environment of merging and exiting on the highway did depend on the interaction with surrounding vehicles which was hard to determine in a predefined scenario.

Overtaking & side-way movements

Yang, Jaeger & Mourant (2006) investigated the driving behavior of novice and experienced drivers while performing lane change maneuvers in a fixed-base driving simulator. The researchers conclude that the study's driving simulator did not duplicate a blind spot. Having this blind spot seemed to be important to perform a left lane change maneuver. The driving simulator should have a front and rear view, including a blind spot, to provide transferable results.

The research of Pan & Shen (2022) conducted a driving simulator experiment to assess the driving risk of novice drivers during the overtaking maneuver on two-lane highways. As a result of the research, the participants reported that they did not feel any differences between driving in the driving simulator while performing the overtaking maneuver compared to driving on the real road. This research result did indicate transferable driving simulator results of drivers performing the overtaking maneuver in a simulated world compared to the real world.

Regarding the examination of driving performance, the research findings of Pawar, Nagendra & Velaga (2021) study showed that a fixed-base driving simulator could provide continuous data on the following aspects under time pressure conditions: longitudinal and lateral speed, acceleration, and lane position. Therefore, the findings of this study could indicate that there are possibilities to improve a fixed-base driving simulator to let it provide transferable results in the future. The earlier mentioned blind spot by Yang, Jaeger & Mourant (2006) is required at least.

Special road sections

The research of Landry et al. (2018) did investigate the driving behavior at highway-rail crossings, which was studied in real-world crossing scenario’s using a driving simulator. The study concluded that the driving simulator was able to simulate representative crossings. Thereby, the study suggested that the driving simulator participants understood what they had to do regarding safety around crossings without warning signals. The research findings did not confirm the transferability of the driving simulator results. However, the results did indicate that transferability could be possible to prove in the future.

Another research that seemed to show promising results regarding the transferability of driving simulator results for railway crossings is the study of Larue, Blackman & Freeman (2018). The study used a driving simulator to measure the rule violations around railway-level crossings objectively. The risky behavior could be measured successfully in different scenarios developed in an advanced driving simulator. Therefore, these results indicated the possibility of transferable driving simulator results regarding future railway crossing driving behavior in a simulator.

In contrast with the promising previous two research findings, the most recent research by Parkin et al. (2022) concluded that differences around pedestrian crossings interaction perceptions between the driving simulator and the real road did depend on the complexity of the maneuver. Thereby, the study concluded that there should be a need for caution in reliance on simulator-only experiments regarding priority-based maneuvers around intersections. Therefore, this study shows less promising results for the transferability of driving simulator results.

Special road maneuvers

Regarding special driving maneuvers like reversed parking Yukawa, Sonoda & Wada (2020) focused on driving simulator tests for steering and timing as possible factors for reversed parking improvement. The study concluded that manual driving would be present in the foreseeable future despite the development of new technologies. Thereby, the advancement of the driving simulator technologies still had implementation challenges. Additional sources about the transferability of driving simulator results were not found in the literature research.

4.8.2 Reliable driving simulator results

Start driving test

According to Wang et al. (2010), using different navigation devices led to a more significant distinction on the road than in the simulator, suggesting that the duration times of this particular driving task differ less under the same circumstances in the simulator than in the real world. It is questionable whether or not the results are reliable.

Straight and curvy roads

During their research to investigate whether or not the simulator driver's behavior matches the real road driving behavior, Gemonet et al. (2021) did conclude that drivers have a greater tendency to show better compliance with speed limits on simulated roads than in the real world. Therefore, simulator drivers seemed to show more consistent driving behavior for this speed limit factor than real road drivers. On the other hand, driving on both straight and curvy roads in a simulator could cause simulator sickness for the drivers. When this phenomenon occurs, their driving performance will be influenced, and therefore the reliability of their driving results as well. In terms of the reliability of driving performance results, the mental workload in a driving simulator could cause more significant speed variability for both road types in a driving simulator compared to the real road.

The research of Blana & Golias (2002) did investigate the differences in lateral displacement for straight and curved roads in a driving simulator and on the road. They found that higher speed on curved roads and lower speed on straight roads increased the mean vehicle lateral displacement in a simulator. This indicated that straight roads with lower speed limits or curved roads with higher speed limits did increase the variability of the lateral displacement on the road. Therefore the reliability of the results could decrease.

Schiro et al. (2014) researched the steering wheel position while driving on straight and curved roads in a driving simulator. The research results showed a more significant variance in the steering wheel positioning and a more significant variance in lane positioning. Therefore, they concluded that a greater accuracy for lane-keeping performance in the car could be found compared to the simulator. Consequentially, the variability of lane-keeping performance results is more significant in the simulator than on the real road.

Driving near and around intersections

There was no information found in the literature research results for the reliability of driving simulator usage for neither measuring the driving task nor assessing the driving performance around intersections via driving skills that are required.

Merge and exit on the highway

Regarding the reliability of driving simulator results, barely any information was available in the literature. Bernadin et al. (2018) investigated the eye and head movement behavior of drivers performing a lane merging task on the highway during multi-tasking using a driving simulator. The research concluded that the nature of an individual driver plays an essential role in this gaze behavior; therefore, differences were found in the driving simulator for specific drivers. Thus, the reliability of driving simulator results was difficult to determine.

Overtaking & side-way movements

Wang et al. (2010) investigated whether there were differences in lateral control and standard deviation of lane positioning between the simulated and on-road environments. A significant effect was found for the standard deviation of lane positioning, which was higher for the simulator than on the road. The higher standard deviation in the driving simulator could result in a greater variety of lane positioning amongst drivers under the same predefined circumstances. The reliability of simulator results therefore decreases.

On the other hand, the research of Pan & Shen (2022) used the driving simulator to assess the driving risk during the overtaking maneuver on a highway and discovered that a small amount of the experiment participants suffered from simulator sickness. When drivers suffer from simulator sickness, the driving simulator results could differ under the same circumstances and therefore lower the reliability.

Special road sections

Regarding the reliability of driving simulator results, Dozza et al. (2020) did investigate the driver's response process while negotiating an intersection with a pedestrian using a fixed-base driving simulator. However, the results showed that it remained unknown if inexperienced drivers did behave more realistically in a driving simulator than experienced drivers. Therefore, the reliability of the driving simulator results remained unclear since deviations from realistic driving behavior could be expected, and it is not known in which driving experience category.

Another research investigating the interaction process around pedestrian crossings is from Sadraei et al. (2020). The results show that measuring braking behavior in terms of speed, acceleration, and distance to pedestrians in simulators is a safe and reliable method for these interactions. The literature research results indicate reliable results for these specific research circumstances regarding the type of intersections studied.

Special road maneuvers

The reliability of driving simulator results for special road maneuvers was challenging in terms of research that had been done to investigate it. Therefore, the research results of Yukawa, Sonoda & Wada (2020) did conclude that despite the recent developments of the driving simulator technology, manual driving will be present in the foreseeable future for performing road maneuvers like reversed parking.

4.8.3 Valid driving simulator results

Start driving test

The driving simulator can be assessed as valid for the start of the driving test when its validity is ensured for the visual limits of humans and their perceptions (Zhao & Sarasua, 2018). The display resolution should result from a visual fidelity that matches reality in terms of resolution and field of view. A more excellent display resolution than reality does not significantly affect speed choice and lane position, whereas widening the field of view does. The simulator mock-up should be similar to an in-car set-up to achieve the same glance behavior and speed variability as on the real road (Klüver et al., 2016). Mayhew et al. (2011) even suggested that the objective assessment of the driving simulator for driving performance could lead to improvement compared to the examiner assessments on the road. However, every single simulator that will be used must be validated in the first place.

Straight and curvy roads

Sahami & Sayed (2013) did investigate what factors could influence the adaptation of a driving simulator to increase its validity. They concluded that a driving simulator scenario on a straight road segment with a constant speed limit did not seem proper to achieve valid driving performance results.

The research of Wang et al. (2010) did draw a few conclusions about the driving simulator validity for gaze behavior during driving on the simulator compared to the real road. Relative validity was found for the total glance duration in a simulator compared to the road while entering the destination on a routing device as a secondary task besides driving. The research even concluded that using a touch screen as a route destination device showed relative and absolute validity since there was a slight underestimation of glance duration in both simulated and real worlds. Both relative and absolute validity was also found for the percentage of time that the eyes were focussed on the road during short time intervals of 30 seconds while performing the route destination entering as a secondary task in the simulator and on the real road. The total number of long off-road glances (longer than 1,6s) also showed relative validity between the driving simulator and the real road under the research circumstances, as explained.

Wang et al. (2010) investigated the longitudinal control regarding speed differences between the simulator and the road. They found relative validity for the longitudinal control of mean speed for which no distinction between different types of vehicles or simulator devices should be made.

Gemonet et al. (2021) did conclude that there is an essential assumption regarding the compliance of driving simulator performance results in a simulator compared to the real road. Namely, driving simulator adaptation is critical for matching simulator results with the real road. The simulator adaptation depends on the type of road involved, which means that valid results for both road types together on the same driving simulator are challenging. Therefore, there is a need to distinguish driving performance on straight and curved roads.

Kaptein, Theeuwes & van der Horst (1996) performed research that mainly focussed on assessing driving behavior in a simulator in terms of validity. First, they concluded that a medium-fidelity fixed-base driving simulator is limited for assessing driving behavior. Secondly, they found relative validity for behavioral variables for driving speed and lane-keeping performance. However, absolute validity could not be achieved. Thirdly, they found that drivers show the same behavior in a driving simulator for route choice decisions compared to the real road, which results in absolute validity.

Driving near and around intersections

One of the findings in the literature about driving simulator validity for driving performance near and around intersections is based on the research of Zöller, Abendroth & Bruder (2019). The research found that a low-fidelity driving simulator was unsuitable for reproducing valid braking behavior.

In 2011 Montella et al. did investigate the driving behavior around rural intersections in terms of speed, deceleration, and lateral positioning using a driving simulator. Montella et al. (2011) concluded that the use of driving simulators for driving around rural intersections did have shortcomings like simulator sickness and the level of realism, which both were important to determine the validity of the driving simulator usage.

The research of Robbins, Allen & Chapman (2018) investigated the gap acceptance behavior around intersections. It concluded that the driver's behavior around intersections needs to be examined in a realistic simulator environment to generalize the behavior in the simulator to the real road. Therefore, the fidelity level of the driving simulator should be at least high to provide valid results possibly. The study did find out a more significant gap in acceptance at intersections in front of motorcyclists compared to cars on real roads. This greater gap acceptance for approaching motorcyclists at an intersection was found in high-fidelity simulators, not in medium-fidelity simulators. Therefore, the research findings of Robbins, Allen & Chapman (2018) aligned with the earlier research findings of Montella et al. (2011). Follow-up research by Robbins, Allen & Chapman (2019) investigated drivers' visual attention at intersections in a driving simulator compared to the real road. The research found evidence that a high-fidelity simulator would be valid regarding drivers' visual attention at intersections.

Merge and exit on the highway

No research was found in the literature on the validity of driving simulator results in terms of merging and exiting the highway.

Overtaking & side-way movements

Relative validity was found by Wang et al. (2010) for the comparison of lateral control and the standard deviation of lane positioning between the simulator and the road. On the other hand, the study of Pan & Shen (2022) determined that the research could have biased results since it was concluded that the driving simulator experiment could diverge from the real driving conditions. In case of biased results, the driving simulator experiment would assess the driving risk during the overtaking maneuver on the highway differently from driving on the road. The results' validity in case drivers are biased could be questioned.

Special road sections

Information about the validity of driving simulator results regarding special road intersections seemed rare, given the requirements of this research. The only source that was found and was available was the study of Landry et al. (2018). While investigating the driving behavior around highway-rail crossings, it became clear that the study could not provide a valid representation of real-world driving behavior around these intersections.

Special road maneuvers

Pawar, Velaga & Sharmula's (2022) study compared the driving behavior between the real and simulated world. It assessed the validity of the fixed-base driving simulator used for this research. A sense of realism was found related to the vehicle systems that must be used while performing special road maneuvers like reversed, parallel, and uphill parking. The gearbox of the driving simulator was rated by 66,7% of the participants as very realistic. Additionally, the accelerator and braking system was rated by 60% of the participants as very realistic. Therefore, this study proved that the driving simulator could be used as a valid research tool to investigate the influence of driving conditions during (special) road maneuvers on driving performance.

Other research studies did try to examine whether or not the driving simulator would be able to improve the current reversed driving of drivers. The research of Ohama et al. (2021) did use a display-based driving simulator. It concluded that the results could indicate that the driving simulator could change the reversing position and improve the reversed parking. However, the study could not prove it. Consequently, the research findings showed similar results as Yukawa, Sonoda & Wada's (2020) research that concluded that the driving simulator technology could improve reversed parking, but not without manual driving until the foreseeable future.

On the other hand, there are high-order driving skills while performing driving maneuvers. Tsapi, Vissers & Buuron's (2022) explorative research tried to investigate the opportunities to train, test and assess these skills to improve road safety. The research concluded that the driving simulator already had proven to improve high-order skills in training and that the driving simulator seemed to be a valid tool to measure high-order skills compared to the current practical driving test.

4.9 Fill in the research framework

This paragraph shows the information found in the literature research to answer the relevant questions in the framework. The framework has been filled in with information for each part of the Dutch driving test. For some parts of the driving test, there are remaining information gaps that could be filled with practical information. For other parts of the driving test, practical information could be added to the information from the literature. The selection of a relevant set of questions of the framework was based on information found on the initial question on the higher level. For example, if the information available on the first question of the frameworks resulted in a ”yes” answer, the follow-up question in the framework for which information was searched would be: “ Have the driving skills been assessed in a driving test on the simulator?” Tables 13 until 19 show the framework results for each part of the Dutch driving test after filling it in with relevant information from the literature research.

Table 13

Framework results: Start driving test

Question from framework	Yes/no / not applicable / no information available	Sources with information	Concluding framework result
Could the set of driving skills be measured in a driving simulator?	No information is available on a complete set of required driving skills	-	-
Could one or more particular aspect(s) of the driving skill(s) be measured in a driving simulator?	Yes	Klüver et al., (2016) and van der Meulen, Kun & Janssen (2016); Wang et al., (2010)	Follow-up questions are asked in the framework
Have driving skills been measured in a test on the driving simulator?	Not applicable	-	-
Are training results transferable?	Yes	Meulen, Kun & Janssen (2016)	Training results on driving simulators could be transferable
Are training results reliable?	No information available	Wang et al. (2010)	-
Are training results valid?	Yes	Zhao & Sarasua (2018); Klüver et al. (2016); Mayhew et al. (2011)	Training results on driving simulators could be valid
Are test results transferable?	Not applicable	-	-
Are test results reliable?	Not applicable	-	-
Are test results valid?	Not applicable	-	-

Particular aspects of the complete set of required driving skills are tested in other research. Therefore, the framework searched for information on the usefulness of training results. Based on the available information, the framework results showed transferable, reliable, and valid training results in earlier research.

Table 14
Framework results: Driving on straight and curved roads

Question from framework	Yes/no / not applicable / no information available	Sources with information	Concluding framework result
Could the set of driving skills be measured in a driving simulator?	Yes	Gemonet et al. (2021); Blana & Golias (2002), Erséus, Trigell & Drigge (2015); Schiro et al. (2014); Kaptein, Theeuwes & van der Horst (1996); Wang et al. (2010); Robbins, Allen & Chapman (2019); Feng et al. (2020)	Follow-up questions are asked in the framework
Could one or more particular aspect(s) of the driving skill(s) be measured in a driving simulator?	Not applicable	-	-
Have driving skills been measured in a test on the driving simulator?	Yes, only in the research of Gemonet et al. (2013), not in other research	Gemonet et al. (2021)	-
Are training results transferable?	No	Klüver et al. (2016); Sahami & Sayed (2013); Gemonet et al. (2021); Blana & Golias (2002); Robbins, Allen & Chapman (2019); Ronen & Yair (2013)	Training results on the driving simulator are most likely not transferable
Are training results reliable?	No	Gemonet et al. (2021); Blana & Golias (2002); Schiro et al. (2014)	Training results on the driving simulator are most likely not reliable
Are training results valid?	Yes	Sahami & Sayed (2013); Wang et al. (2010); Gemonet et al (2010); Kaptein, Theeuwes & van der Horst (1996)	Relative validity was found for training results on a driving simulator
Are test results transferable?	No information available	-	Research by Gemonet et al. (2021) shows positive results, but no specific information on transferability
Are test results reliable?	No information available	-	Research by Gemonet et al. (2021) shows positive results, but no specific information on the reliability
Are test results valid?	No information available	-	Research by Gemonet et al. (2021) shows positive results, but no specific information on the validity

The framework results show that information is available on driving simulator training results. Driving simulator training results do not seem useful for assessing driving performance on the real road. In addition to Gemonet et al. (2021) research, more information is needed on driving simulator test results.

Table 15
Framework results: Driving near and around intersections

Question from framework	Yes/no / not applicable / no information available	Sources with information	Concluding framework result
Could the set of driving skills be measured in a driving simulator?	No	-	-
Could one or more particular aspect(s) of the driving skill(s) be measured in a driving simulator?	Yes	Eden, Tanguiam & Palmiano (2021); Robbins, Allen & Chapman (2018), Robbins, Allen & Chapman (2019); De Winter, De Groot, Spek & Wieringa (2009); González-Ortega et al. (2018); Zöller, Abendroth & Bruder (2019)	Follow-up questions are asked in the framework
Have driving skills been measured in a test on the driving simulator?	No	-	-
Are training results transferable?	No	González-Ortega et al. (2018); De Winter et al. (2009); Zöller, Abendroth & Bruder (2019)	Training results on the driving simulator are most likely not transferable
Are training results reliable?	No information available	-	-
Are training results valid?	Yes	Zöller, Abendroth & Bruder (2019); Montella et al. (2011); Robbins, Allen & Chapman (2018); Robbins, Allen & Chapman (2019)	Training results on the driving simulator could be valid
Are test results transferable?	Not applicable	-	-
Are test results reliable?	Not applicable	-	-
Are test results valid?	Not applicable	-	-

The framework results show no information on the reliability of driving simulator test results is available. On the other hand, promising results are found in the literature regarding the validity of driving simulator training results. High-fidelity driving simulators are recommended.

Table 16

Framework results: Merge & exit on the highway

Question from framework	Yes/no / not applicable / no information available	Sources with information	Concluding framework result
Could the set of driving skills be measured in a driving simulator?	No	-	-
Could one or more particular aspect(s) of the driving skill(s) be measured in a driving simulator?	No information available	-	-
Have driving skills been measured in a test on the driving simulator?	Not applicable	-	-
Are training results transferable?	No	Yamada, Matsuyama & Uchida (2014)	Driving simulator training results seem not transferable
Are training results reliable?	No	Bernadin et al. (2018)	Driving simulator results seem not reliable
Are training results valid?	No information available	-	-
Are test results transferable?	Not applicable	-	-
Are test results reliable?	Not applicable	-	-
Are test results valid?	Not applicable	-	-

Information about this merging and exiting on the highway regarding driving on a simulator seemed challenging. The framework results show that there was barely any information available, which leaves the framework with multiple knowledge gaps.

Table 17

Framework results: Overtaking and side-way movements

Question from framework	Yes/no / not applicable / no information available	Sources with information	Concluding framework result
Could the set of driving skills be measured in a driving simulator?	No	-	-
Could one or more particular aspect(s) of the driving skill(s) be measured in a driving simulator?	Yes	Bergeron et al., (2006); Yang, Jaeger & Mourant (2006); Wang et al. (2010); Pawar, Nagendra & Velaga (2021); Pan & Shen (2022)	Follow-up questions are asked in the framework
Have driving skills been measured in a test on the driving simulator?	Not applicable	-	-
Are training results transferable?	Yes	Yang, Jaeger & Mourant (2006); Pan & Shen (2022); Pawar, Nagendra & Velaga (2021)	Driving simulator training results could be transferable
Are training results reliable?	Yes	Wang et al. (2010); Pan & Shen (2022)	Driving simulator training results could be reliable
Are training results valid?	Yes	Wang et al. (2010); Pan & Shen (2022)	Relative validity was found for driving simulator training results
Are test results transferable?	Not applicable	-	-
Are test results reliable?	Not applicable	-	-
Are test results valid?	Not applicable	-	-

The driving simulator seems able to provide positive results on the driving simulator trilogy for training results. Therefore, using driving simulators to assess driving performance for overtaking and side-way movements seems promising. However, the framework shows that information on testing with driving simulators is unavailable.

Table 18
Framework results: Special road sections

Question from framework	Yes/no / not applicable / no information available	Sources with information	Concluding framework result
Could the set of driving skills be measured in a driving simulator?	No	-	-
Could one or more particular aspect(s) of the driving skill(s) be measured in a driving simulator?	Yes	Landry et al. (2018); Parkin et al. (2022); Larue, Blackman & Freeman (2018); Dozza et al. (2020); Sadraei et al. (2020)	Follow-up questions were asked in the framework
Have driving skills been measured in a test on the driving simulator?	No	-	-
Are training results transferable?	No	Landry et al. (2018); Parkin et al. (2022); Larue, Blackman & Freeman (2018)	Driving simulator results are most likely not transferable
Are training results reliable?	Yes	Sadraei et al. (2020); Dozza et al. (2020)	Under specific circumstances, the driving simulator training results are reliable
Are training results valid?	No	Landry et al. (2018)	Driving simulator results are most likely not transferable
Are test results transferable?	Not applicable	-	-
Are test results reliable?	Not applicable	-	-
Are test results valid?	Not applicable	-	-

Based on the conclusions of the framework, it doesn't seem easy to find concrete information on special road sections and driving simulator usage. Each special road intersection has different characteristics to consider, which results in a wide variety to cover with driving simulators. Some research did investigate a particular traffic phenomenon at special road sections using the driving simulator. However, these did not focus on the driving simulator as a research subject. There are multiple knowledge gaps left in the framework.

Table 19

Framework results: Special road maneuvers

Question from framework	Yes/no / not applicable / no information available	Sources with information	Concluding framework result
Could the set of driving skills be measured in a driving simulator?	No	-	-
Could one or more particular aspect(s) of the driving skill(s) be measured in a driving simulator?	Yes	Pawar, Velaga & Sharmila (2022); of Ohama et al., (2008) and Yukawa, Sonoda & Wada, (2020)	Follow-up questions are asked in the framework
Have driving skills been measured in a test on the driving simulator?	No	-	-
Are training results transferable?	No	Yukawa, Sonoda & Wada (2020)	Driving simulator training results are most likely not transferable
Are training results reliable?	No		
Are training results valid?	Yes	Pawar, Velaga & Sharmula (2022); Ohama et al. (2021); Yukawa, Sonoda & wada (2020); Tsapi, Vissers & Buuron (2022)	Driving simulator training results could be valid
Are test results transferable?	Not applicable	-	-
Are test results reliable?	Not applicable	-	-
Are test results valid?	Not applicable	-	-

The framework results show that driving simulator training results could be valid for different special road maneuvers. Regarding the usefulness of driving simulator training, research indicates that human presence is required in the foreseeable future. On the other hand, information on testing with driving simulators seems unavailable according to the framework.

The results of the literature research shown in Tables 13 to 19 are summarized in Figure 5. Each driving test part corresponds with the following number in Figure 5:

1. Start driving test
2. Driving on straight and curved roads
3. Driving around intersections
4. Merge and exit on the highway
5. Overtaking and side-way movements
6. Driving at special road sections
7. Performing special road maneuvers

For some driving test parts, particular sources showed positive and negative results on the driving simulator trilogy. Therefore, a straightforward answer to the questions in the framework was more challenging to find. The assumption has been made that the answer was “no” when there were ambiguous results.

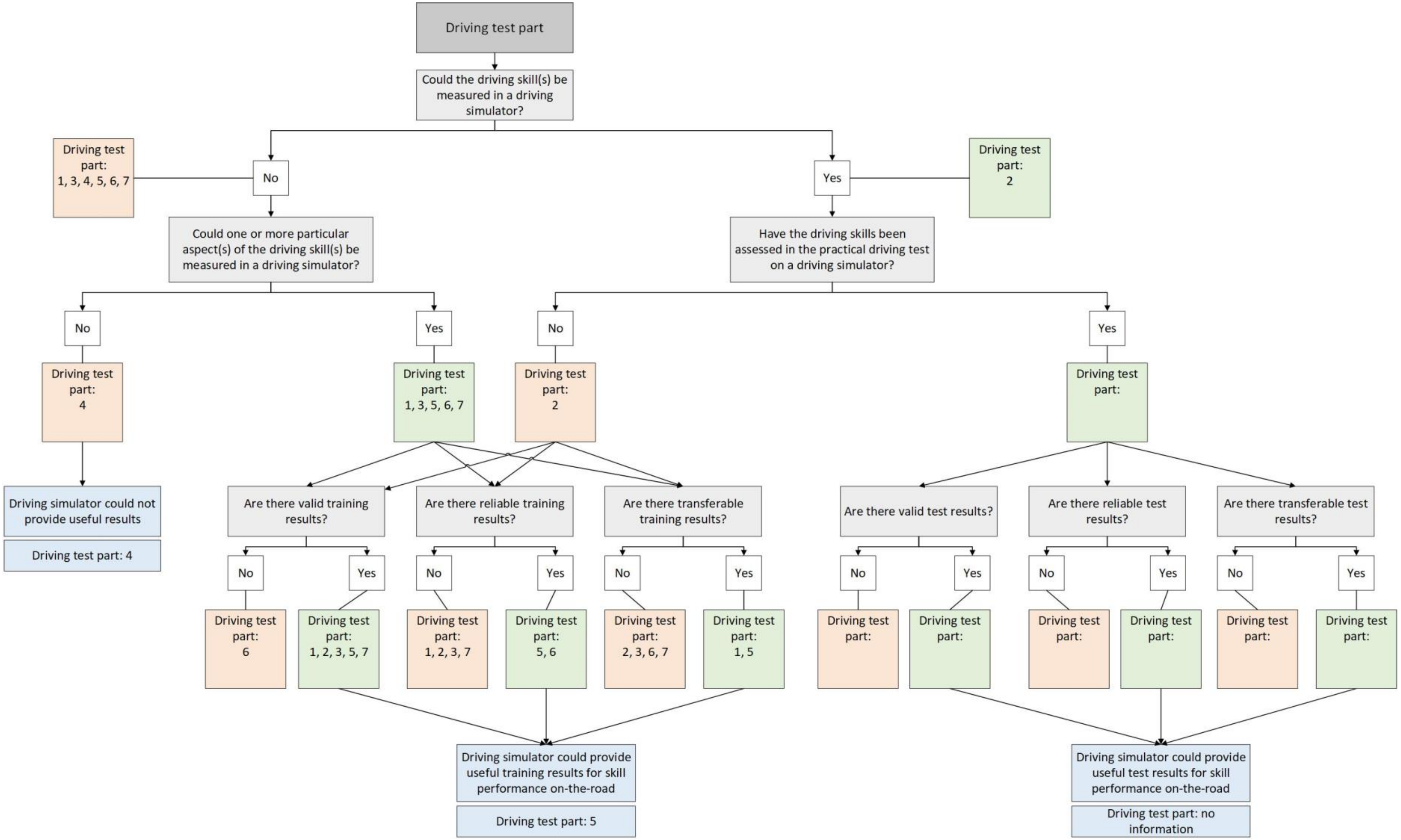

Figure 5

Filled-in research framework with information from the literature research

Not. Own work

5. Results questionnaire & interviews

The framework results of the literature research, as shown in paragraph 4.9. are the input to start the questionnaire. A questionnaire was spread amongst CIECA members to fill in the remaining knowledge gaps in the framework for each part of the driving test. This chapter shows the questionnaire results together with the follow-up interviews. Paragraph 5.1 shows the list of CIECA members that answered the questionnaire. The questionnaire results were used to determine which countries were asked to participate in follow-up interviews. The list of questions asked to each chosen CIECA member was determined by the information gathered from the questionnaire. In paragraph 5.2, the interview results of the selected CIECA members are shown. Paragraph 5.3 includes a summary of the questionnaire and interview results. Paragraph 5.4 summarizes the knowledge gaps in the framework. The finishing paragraph 5.5 does offer insights from a separate interview with a Product Manager CCV at the CBR. The information concerns a pilot study on driving simulator assessment of driving skills required for performing special maneuvers by truck drivers while driving on a closed-off terrain. The Product Manager CCV shares the information about the pilot at the CBR. The CCV division is responsible for making the driving tests for professional drivers and the examination (Divisie CCV, 2022).

5.1 A questionnaire amongst CIECA members

The questionnaire was spread amongst all effective CIECA members from 30 June until 18 August. Exactly 18 out of the 36 members responded to the questionnaire, a response rate of 50%. Table 20 shows every CIECA member that responded, whether or not driving simulator research has been done in the field of driving testing. Significant remarks mentioned at the end of the questionnaire are shown in Table 20 as well.

Table 20
CIECA members that responded to the questionnaire

Country responded	Research done on practical driving test simulator	Special Remarks	Follow-up interview
Iceland	No	No	No
Bulgaria	No	No	No
Belgium (Flanders)	No	Used for learning basic principles of driving a truck, used by *VDAB* in Flanders (Vlaamse Dienst voor Arbeidsbemiddeling)	No
Germany	No	No	No
Austria	No	No	No
Georgia	Yes	No	No
Luxembourg	No	Only used in the national center for functional re-education and rehabilitation	No
Northern Ireland	No	No	No
Ireland	No	No	No
Estonia	Yes	No	Yes
Faroe Islands	No	No	No
Sweden	Yes	Take further steps towards implementing simulators in driving tests and unify and improve the use of simulators in driving education.	Yes
Netherlands	No	Initial explorations regarding suitability for simulator usage in professional qualification for professional drivers, more specifically, the confined terrain test.	No
Romania	No	No	No
Czech Republic	No	No	No
Finland	No	Research done related to measuring the performance of driving skills in training for other purposes	Yes
Hungary	No	No	No
United Arab Emirates	No	No	No
Great Britain	No	Transport research laboratory in the UK researches the use of driving simulator training	No

5.2 Interviews: Finland, Estonia & Sweden

The interviews were conducted to gain insight into the driving simulator usage experiences for driving training and testing within countries other than the Netherlands. Concerning the usefulness of driving simulators, the views of experts in training and testing were studied. The questionnaire results revealed which countries have experience with driving simulator usage for training and testing. Therefore, the answers to the questionnaire questions are the information input for the interviews. As a result, three countries were invited for a follow-up interview: Finland, Estonia, and Sweden. Even though Georgia answered that there is some experience with research on a simulator's driving test results, the country was not selected due to the delayed response. After the second reminder was sent out to the respondent of Georgia, the decision was made not to select Georgia for in-depth follow-up interviews anymore because the whole research process would have been delayed for a few weeks. However, contact with the respondent of Georgia did finally take place. Even though the decision has been made not to wait for a response anymore, the respondent of Georgia did let the researcher know to be interested in the research and was open to answering questions if needed. The researcher informed the respondent about the decision to avoid further delay for the rest of the research process.

5.2.1 Finland

The rationale behind the decision to ask Finland for a follow-up interview is that they explicitly responded that they had researched measuring driving skills during training and education, which could directly be related to the sub-question: "*What is the measurability of the required driving skill(s) for the particular practical driving exam part regarding the driving performance in the driving simulator?"*. The organization representing Finland as an effective member of CIECA is the *Traficom Finnish Transport and Communications Agency* (Traficom). The organization strives to build operational reliability. The goal is to move data and goods smoothly, securely, and sustainably (Traficom, n.d.).

The specific questions in the online interview are focused on how driving skills are measured during the research Finland has conducted in the past. Thereby, questions are asked about the specific training elements for which driving simulators are used together to use them. Additionally, questions about the predictivity of driving simulator training results for real road performance are asked. In conclusion, the final question is about a future perspective for driving simulator usage based on Finland's experiences with it so far. An employee of Traficom answered the questions online. The following questions were asked:

1. What are your experiences in Finland with driving simulators used for training and/or education so far?
2. For what training or education purposes did you use driving simulators in Finland?
3. How did you measure the performance of particular driving skills during training in the simulator?
4. Are the driving simulator performance skills in training predictive for training on the real road? Concerning the validity/ reliability and transferability of the results.
5. Why did you do nothing with driving simulators in the actual driving test so far in Finland?
6. Concerning your experiences with driving simulator usage, do you think there is an opportunity for the driving simulator to be a useful driving test tool in the future?

The results of the interview questions to Finland are presented in Table 21. A quote that was part of the answer is written down for each question. These quotes represent the object of interest for each question.

Table 21
Results interview questions Finland

Question	Quote
Q1	"Since 2018, the use of simulators has been possible for any content of the compulsory training in category B. This greatly boosted the training sector to develop new simulators and programs."
Q2	"Since 2018, simulators can be used for anything like learning basic car handling skills, driving in the city, defensive driving, etc. It is even possible to take a driving test and never has been driving a real car before until the driving test."
Q3	"Nowadays, risk education is mostly done with simulators."
Q4	"The results do not show a statistically significant superiority of the simulator in teaching, but it does show a strong indication that the use of the simulator does not have negative effects on the learning outcomes when the issue is considered in passing the driver's license driving test with probability."
Q5	"Simulator is never as good as a real traffic environment with all different participants. Traffic is an interaction and a social activity. A driver does not act in a vacuum; they must pay attention to the other participants, and anticipation is essential."
Q6	"For now, I do not see it especially useful in the driving test. Many people get physical symptoms, and the simulator is never as good as the real environment."

Finland has used driving simulators since 2008 for compulsory training in category B (private car). However, the use of simulators was highly regulated in the first decade. Driving simulator usage was restricted to training under challenging conditions like driving in darkness. Since 2018, using driving simulators has been possible for any content of the compulsory training in category B. This gave a significant boost in Finland to develop new simulators and programs. It is now possible to train many skills and competencies in a simulator. So far, most experiences are positive. Some people seem to benefit from it, and others do not. However, there is a portion of students that gets physical symptoms like dizziness, headaches, or visual disturbances with simulators.

Since 2018 driving simulators have been widely used for different training and education purposes in Finland. The simulators are used for anything like learning basic car handling skills, driving in the city, defensive driving, etc. In Finland, it is even possible to take a driving test and never have been driving a real car before until the driving test. An important part of the driving education program is risk education. Nowadays, risk education is mainly done with simulators. In Finland, slippery track practices are an important part of risk education. The slippery track practices on the real road have been turned into practices in the simulator, which seem to positively affect traffic safety concerning young driver accidents in icy driving conditions. The simulator exercises are generally placed in the curriculum to support teaching the same content areas provided by other means.

Conclusions about the predictivity of performance skills in driving simulator training for real-road performance are hard to draw, according to the contact person of Finland. However, the contact person referred to a small study performed at the University of Turku that concluded a weak correlation between the number of simulator drives and the probability of passing the driver's license test, which is not statistically significant. The results of this study do not show a statistically significant superiority of the simulator in teaching. Still, it strongly indicates that using a simulator does not negatively affect learning outcomes when the issue is considered in passing the driver's license driving test.

The benefits of using the driving simulator in the teaching program in Finland seem to be: a restrained driving style, standardizability of teaching software, traceability of the learning process, the accuracy of feedback, and a unified knowledge and skill base for the traffic teachers supervising the teaching. Another benefit seems to be that it brings cost efficiency compared to formal driving lessons. However, driving examiners in Finland noticed that students who had a lot of driving simulator training and not much practice with the real car had problems in the examination for the car's dimensions. This resulted in minor accidents like breaking the side mirror of another car when parking or driving too close to a parked car, with no significant problems.

Despite positive experiences with driving simulator usage in training and education, they have not been used in the driving test in Finland. According to the contact person, there are several reasons for that. The simulator is never as good as the real environment in terms of a constantly changing environment because the participants are different each time. A driver does not operate in a vacuum. They continuously have to pay attention to other participants; anticipation is an essential part of that. Therefore, in Finland, a simulator is considered a training tool and seems very promising to be useful for specific tasks for particular students who need special attention or practice for personal reasons.

The representative who answered the interview questions for Traficom in Finland does not consider the driving simulator a useful tool for the driving test. Many people get physical symptoms such as dizziness, headache, and visual disturbances with simulators. The representative does not value the simulator or the real traffic environment concerning all participants. However, the representative believes there are opportunities for the driving simulator to be valuable to the category B driving program, but not as a substitute measuring tool for driving skills during the driving test.

5.2.2 Estonia

Estonia is one of the two effective members besides Sweden that answered "yes" to the question of whether or not they were aware of any research on the practical driving test conducted on a simulator in their country. Therefore, Estonia is one of the three countries selected for a follow-up interview. The company that represents Estonia as an effective member of CIECA is *Transpordiamet.* The company oversees traffic education, mobility, and transport in Estonia (*Republic of Estonia: Transport Administration*, n.d.).

Since Estonia has no experience with driving simulator tests, an interview could be relevant for several sub-research questions. The relevance depends on the level of detail that was carried out during the research in Estonia. For example, sub-questions about the transferability, reliability, or validity of the driving simulator could be irrelevant when the research in Estonia did not investigate these factors.

The content of the asked questions is based on the rationale to discover at which stage the driving simulator usage research is right now. What are the research findings and conclusions about the usefulness of driving simulator usage? Since Estonia did not explain what kind of research they have conducted already, the interview questions are meant to discover that. Thereby, important factors like the research's transferability, reliability, and validity are being questioned. In the end, the same holds for Sweden and Finland; the question is asked what their future perspective is based on their research experiences so far. The questions that are asked to a representative of Transpordiamet are listed below:

1. What are your experiences in Estonia with driving simulators used for training and/or education so far?
2. What training goals and education purposes do you use driving simulators in Estonia?
3. How did you measure the performance of particular driving skills in the driving simulator?
4. Are the driving performance results of driving skills during training predictive for training results on the real road? Concerning the validity/ reliability/ and transferability of simulator results compared to results on the real road?
5. What are your experiences with driving simulators used for the actual driving test so far?
6. Why do you want to use the driving simulator on the actual driving test?
7. Do you think that driving simulation performance results of driving skills in the actual driving test could predict the test results on the real road?
8. Concerning your experiences with driving simulator usage, do you think there is an opportunity for the driving simulator to be a useful driving test tool in the future?

The results of the interview questions about Estonia are presented in Table 22. A quote that was part of the answer is written down for each question. These quotes represent the object of interest for each question.

Table 22
Results interview questions Estonia

Question	Quote
Q1	"Trainers are using simulators for mandatory night-time driving (1 hour)."
Q2	"We want to know if we can use driving simulators in other fields. We want to know if simulators really work. Therefore we can use simulators not only for night-time driving but for other purposes as well."
Q3	"Our research has not focused on measuring particular driving skills while using the driving simulator."
Q4	"We have not done any survey linked to our research to learn more about the reliability/transferability or validity of driving simulator usage."
Q5	"We have not used the driving simulator in the actual driving test until so far."
Q6	"We are interested in using it probably in the future, but we do not have a particular reason to implement the driving simulator for the driving test right now."
Q7	"We have not done any research so far."
Q8	"Yes, probably in the future."

In Estonia, driving trainers are using simulators for mandatory night-time driving, in other words learning to drive under more difficult circumstances. Estonia wants to explore whether the driving simulator works in other fields besides the mandatory night-time drive testing. The representative of Transpordianet said that they had not conducted any survey to discover whether or not driving simulator usage for night-time driving is valid. As a result, Estonia seems interested in developing opportunities for advanced driving simulator usage in the future. Therefore, it believes it could be a valuable tool for the driving test. However, at this moment, the research in Estonia still seems to be a bit in its infancy.

5.2.3 Sweden

The justification for selecting Sweden as one of the countries interesting for a follow-up interview is that Sweden is working on a project, which is not finished yet, that aims to take further steps into implementing simulators in the driving test and to unify and improve the use of driving simulators in driving education. Since the project is unfinished, only the findings so far are shared in the interview.

One of the organizations that are representing Sweden as an effective CIECA member is *Trafikverket*. The organization is one of the Swedish Transport Administration's traffic safety experts. The organization will also coordinate the implementation of the UN's global plan for road safety (*Trafikverket*, n.d.). An employee of Trafikverket answered the questions in the online interview.

Since the Swedish project investigates the same research objective as in this thesis report, the specific interview questions are mainly focused on the content of the Swedish project to gain new insights. Therefore, every sub-question is connected to at least one of the interview questions. The following questions are asked:

1. What are your experiences with driving simulator usage in training and education for learning how to drive a car?
2. What driving skills could be measured in a simulator concerning the validity/ reliability and transferability of driving performance compared to the real road?
3. What is the most important reason(s) to investigate driving simulator usage for the actual driving test?
4. Could you tell me more about the project you are currently conducting toward implementing driving simulators in the actual driving test?
5. What are the project results until now?
6. What kind of driving simulator is used during the project?
7. Why do you think a consequence here would be an increased degree of passing the driving test because there are situations that cannot be tested in the standard driving test? Is the driving simulator representative compared to the real road here?
8. Do you think the driving simulator could provide predictive driving test results compared to the driving test results in a real car?
9. For which parts of the driving test do you think the driving simulator could be used best to gain the most significant results for improving road safety and hazard perception?

The results of the interview questions to Sweden are presented in Table 23. A quote that was part of the answer is written down for each question. These quotes represent the object of interest for each question.

Table 23

Results interview questions Sweden

Question	Quote
Q1	"It is a good complement to driving a car. The lessons can be individually designed, controlled, and repeated. The teachers don´t have to sit beside the driver since many things can be practiced alone. It is thus more efficient, safer, and more environmentally friendly."
Q2	"Most important is the hazard perception."
Q3	"To enable a more comprehensive test since it is hard to control what will actually be tested in the present test. With a simulator, we can make a screening to ensure that too risky drivers do not advance to the driving test and thereby may get their driving license before they are ready."
Q4	"We have made a study to evaluate the possibility of identifying risky drivers with a driving simulator; 70 drivers have conducted the test a few days before the driving test. Neither the drivers, the teachers, or the inspectors know the results from the driving test."
Q5	"The most important result is that many pass the driving test although they have shown a very risky behavior in the driving simulator."
Q6	"A fixed-based low fidelity simulator with car seat, pedals, real driving wheel, automatic clutch, and three screens."
Q7	"If we can identify the drivers that are not yet ready and give them more training in what the test has shown necessary, the degree of passing the driving test will increase."
Q8	"No, I think the driving simulator should be used to complement the driving test and never as a replacement."
Q9	"To capture hazard perception. Understanding risky situations and adapting speed and distance after the situations."

According to the representative of *Trafikverket*, using simulators for driving a car has proven to be more efficient, safe, and environmentally friendly than learning how to drive on the real road. Lessons could be individually designed, controlled, and repeated. Therefore, the driving simulator seems to be a good complement to driving a car.

The reason behind the investigation into driving simulator usability for the car-driving test in Sweden is to enable a more comprehensive test since the representative argues that it is hard to control what will actually be tested in the present test. As an elaboration on that argument, the representative explains that with a driving simulator, they can make a screening to ensure that too risky drivers do not advance to the driving test and thereby may get their driving license before they are ready.

Therefore, the Swedish project aims to increase road safety by ensuring that drivers who show apparent deficiencies in hazard perception are detected before the real driving test. Besides the safety argument, the second project aim is that simulators should provide the opportunity to supplement the driving test with situations that cannot be tested in the driving test. According to the Swedish project researchers, these two arguments should lead to an increased degree of passing the driving test when the simulator is implemented. Concerning the driving skills that could be measured in a driving simulator, this project focuses on drivers' hazard perception. In other words, high-order driving skills. The study evaluates the possibility of identifying risky drivers with a driving simulator. During the project, 70 drivers conducted the simulator test a few days before the driving test. Neither the inspectors, drivers, nor teachers know the driving test results. The most important research results until now are that many students pass the driving test even though they showed very risky behavior in the driving simulator a few days before the driving test. However, the project is not finished yet.

Based on the project results so far, the representative concludes that the simulator could complement the driving test. Suppose the simulator can identify the drivers that are not ready and give them more specific training in what the simulator test has shown necessary. In that case, the project researchers aim that the degree of passing the driving test will increase.

As a result of the first interview questions, a second set of interview questions was conducted and asked online. The questions of the second online interview are asked to the same representative who answered the first set of questions for Sweden. These questions aim to get more information about hazard perception concerning the usefulness of the simulator to become a significant addition to the driving test. Additionally, the fidelity level of the simulator is asked to gather more information about the type of simulator usable for testing hazard perception. The second list of interview questions:

I. In general, do you think that novice drivers have to train in driving on a simulator before they take a test on a driving simulator?
II. Do you already use driving simulators to train hazard perception in the first place specifically? If yes, could you elaborate?
III. How do you identify risky behavior?
IV. How do you test hazard perception in the simulator? Which variables did you choose to measure this?
V. Could you explain why you have chosen a specific fidelity type of driving simulator for the research purpose of your project?

The results of the interview questions are presented in Table 24. A quote that was part of the answer is written down for each question. These quotes represent the object of interest for each question.

Table 24
Results second list of interview questions Sweden

Question	Quote
I	"At least they must get used to the simulator before the test starts. It is not the same as driving in real traffic, and they must get familiar with things like speed and graphics."
II	"Several traffic schools in Sweden already use driving simulators in education. They are used as a complement specifically for situations that are difficult to create. Hazard perception connected to these situations."
III	"Driving at too high speed according to the conditions (vulnerable road users, slippery roads, fog, for example). Driving too close to other road users. Not giving way. Not seeing possible risks, for example, when a bus has stopped, someone might cross the road ahead of the bus."
IV	"Speed, distance, if they give way, subjective ratings of performance and risk."
V	"The transportable simulator without moving base is the type mostly used in driver education and the one most likely to implement at driving tests. It is easy to move, inexpensive, and still valid for the purpose."

The Swedish project follows the same thought when learning how to drive a simulator compared to the learning process of driving a real car. They believe that drivers must get used to a simulator before any driving simulator test starts. It is not the same as driving in real traffic; therefore, drivers must get familiar with factors like speed and graphics. The same process holds for drivers who have to get used to driving on the real road in the first place.

Several traffic schools in Sweden already use driving simulators in education. They are used as complements specifically for situations that are difficult to create. Hazard perception is connected to these situations. Thereby, the project aims that the driving simulator could complement the driving test in Sweden. Therefore, hazard perception training on driving simulators and the opportunity for the driving simulator to complement the driving test seem related.

Hazard perception is needed because drivers could show risky driving behavior, resulting in severe accidents. Risky behavior could be an extensive definition; therefore, the representative has been asked to define this concept. Risky behavior is "*driving at too high speed according to the conditions (vulnerable road users, slippery roads, fog, for example), driving too close to other road users, not giving way, not seeing possible risks*." Therefore, speed, distance, or subjective performance ratings are variables to measure risky behavior.

A specific driving simulator type is used during the project to measure hazard perception. A transportable simulator without a moving base is argued to be valid. Thereby, it is not expensive and easy to move. The Swedish driver education uses this type of simulator mostly as well.

5.3 Summary practice results

Three of the 18 CIECA members that responded to the questionnaire were selected for online follow-up interviews: Finland, Estonia, and Sweden. The chosen members answered in the questionnaire that they had any experience with research on simulator driving tests and were available for follow-up questions. The follow-up interview questions differed for each country based on their answers to the preceding questionnaire.

Finland has used driving simulators since 2018 for different training and education purposes. The driving simulators are used there for multiple purposes, like learning basic driving handling skills or driving in a city. Nowadays, the driving simulator is used primarily for hazard perception, affecting traffic safety significantly. Information about transferability, reliability, and validity is still hard to gather.

Despite positive experiences with driving simulator usage in training and education, they have not been used in a driving test in Finland. The representative of Finland did argue that a driving simulator is not considered to use for a driving test right now in Finland.

On the other hand, there is Estonia. Driving simulators are used in Estonia to train nighttime driving. Using the driving simulator for nighttime driving is not validated yet. However, Estonia did report being interested in developing advanced driving simulator opportunities in the future. For now, driving simulator usage is still in its infancy in Estonia. Although the country reported in the questionnaire to have experience with driving simulator testing, the online interview results showed that driving simulator usage is still not very much studied in the country except for nighttime driving.

Sweden has started a project that aims to take further steps into implementing simulators in the driving test and to unify and improve the use of driving simulators in driving education. The project is not finished yet at the moment of writing this thesis. Therefore, Sweden has shared its findings until now. The project set-up is to test exists of 70 drivers who have conducted the driving simulator test on hazard perception a few days before the driving test on the road. Neither the drivers, the teachers, nor the inspectors knew the driving test results. Based on the project findings so far, Sweden believes that the driving simulator could complement the car in terms of a controllable, individual, and repeatable environment that is more environmentally friendly, safe, and efficient. Hazard perception is believed to be the best measurable driving skill. With the project started, a more comprehensive driving test is aimed at hazard perception. It was argued that the drivers must get used to the driving simulator before the test gets started to get familiar with it.

Transferability

According to Finland, the driving simulator can never be as realistic as the real traffic environment regarding other traffic participants. On the other hand, a reference was made to a small study performed at the University of Turku that concluded a weak correlation between the number of simulator drives and the probability of passing the driver’s license test. The results of this study do not show a statistically significant superiority of the simulator in teaching. Still, it strongly indicates that using a simulator does not negatively affect learning outcomes when the issue is considered in passing the driver’s license driving test. Therefore, insights from that study could indicate that future transferable results in a driving simulator test are possible.

Research on the transferability of driving simulator results is still in its infancy in Estonia. However, using driving simulators for nighttime driving could indicate a possibility for transferable driving simulator results in the future.

Sweden did not research the transferability of driving simulator results as a separate research subject. However, this CIECA member believes the driving simulator is a good complement to the driving car.

Reliability

Finland mentions that a significant portion of people suffer from physical symptoms besides the argument that the driving simulator does not represent real traffic situations as on the real road. Therefore, the driving simulator is not especially useful in driving test.

Estonia did not report any research on the reliability of driving simulator results. The usage of driving simulators is still in its infancy.

Several traffic schools in Sweden already use driving simulators in education to train hazard perception. They are used as a complement specifically for situations that are difficult to create hazard perception connected to these situations. Therefore, these results indicate a realistic chance of reliable driving simulator results regarding hazard perception when the reliability of driving simulator results would be a research topic in the future. However, these are assumptions that are not based on research that is done on driving simulator reliability.

Validity

Finland has no research results on the validity of driving simulator tests. At this moment, there is the opinion that the driving simulator environment is not similar to the real traffic environment in terms of representing other traffic users.

Estonia reported no research results regarding the validity of driving simulator results. The driving simulator usage is still in its infancy.

Sweden is researching to create a more comprehensive driving test regarding hazard perception. The driving simulator is used to identify risky drivers for which the current driving test seems invalid. Sweden found that many drivers pass the driving test while showing risky behavior and get their driving license before they are ready. For the project, Sweden used a transportable simulator without a moving base, primarily used in driver education and most likely to be implemented at driving tests. It is easy to move, inexpensive, and still valid for the purpose. Therefore, based on the information from Sweden, this type of simulator is considered valid when hazard perception should be measured in a driving simulator. Regarding driving simulator test results for other parts of the driving test than capture hazard perception, it is believed that the driving simulator should be used as a complement to the on-road driving test and never as a replacement.

5.4 Fill in the research framework

The practical information from the in-depth interviews with Finland, Estonia, and Sweden showed that additional information on the driving simulator's test validity, reliability, and transferability was hard to find. In terms of filling in gaps after filling in the framework for each Dutch driving test part, the interviews did not provide any new information. However, additional information on the usefulness of driving simulator training results related to each part of the Dutch driving test could be added.

Estonia, Finland, and Sweden already use the driving simulator to train in risky driving situations. Estonia uses the driving simulator for nighttime driving. Finland makes use of the driving simulator for slippery track practices. Both countries reported positive experiences with the driving simulator for training hazard perception in these situations. Additional to these findings on simulator training, Sweden reported its belief that the driving simulator could be a promising complement to the actual driving test in terms of testing hazard perception. Therefore, Sweden is researching driving simulator usage as a pre-test to assess hazard perception

Regarding the usefulness of the driving simulator training and test results, practical information showed that training and probably testing hazard perception could be done using a driving simulator instead of training or testing it on real roads. To bring together the practice and literature results, table 25 shows the additional information from the in-depth interviews to fill in the framework.

Table 25
Fill in the research framework with the results from the literature and practice

Car-driving test part	Information from the literature research	Additional information from the in-depth interviews
Start of the driving test	• One or more aspects of the set of driving skills can be measured in a driving simulator • Training results are transferable • Training results are not reliable • Training results are valid	• The driving simulator is being used successfully in the car driving licensing program in Finland and Sweden to train hazard perception • The driving simulator is not believed to replace the on-road test • The driving simulator usage could lead to a more comprehensive driving test in combination with the road • There are no specific experiences with an assessment of transferability, reliability, and validity of driving simulator performance results
Driving on straight and curved roads	• The set of driving skills could be measured in a driving simulator • Training results are not transferable • Training results are not reliable • Training results are valid	
Driving near and around intersections	• One or more aspects of the set of driving skills can be measured in a driving simulator • Training results are not transferable • Training results are not reliable • Training results are valid	
Merge and exit on the highway	• Not enough information is available	
Overtaking and side-way movements	• One or more aspects of the set of driving skills can be measured in a driving simulator • Training results are transferable • Training results are reliable • Training results are valid	
Special road sections	• One or more aspects of the set of driving skills can be measured in a driving simulator • Training results are not transferable • Training results are reliable • Training results are not valid	
Special road maneuvers	• One or more aspects of the set of driving skills can be measured in a driving simulator • Training results are not transferable • Training results are not reliable • Training results are valid	

5.5 Insight from the Dutch truck driving test

To the researcher's knowledge, the car-driving test is not officially performed on a driving simulator in any country. However, CBR in the Netherlands started with a pilot using a driving simulator for the so-called "Toets Besloten Terrein" (TBT). This driving test does assess the driving skills of performing special maneuvers of truck drivers while driving on a closed-off terrain for other traffic users. Although this type of driving test is somewhat different from the car-driving test in terms of the closed-off environment and the sole focus on special maneuvers, the findings of this pilot could be interesting in terms of experiences with driving simulators for measuring particular skills to drive a vehicle.

Using the driving simulator for the TBT is an idea from years ago. However, there were technical problems and simulator sickness (Product Manager CCV at the CBR, personal communication, 4 November 2022). According to the driving simulator manufacturer, this issue is almost solved and not a problem anymore. Additionally, there is the environmental argument for using driving simulators since they do not cause greenhouse gas emissions. Another argument would be the driving schools do have to rent a closed-off terrain for taking the TBT test. The schools also argue that modern vehicle engines are unsuitable for driving at lower speeds and performing special maneuvers for a more extended time; they are developed to drive long distances at higher speeds.

In other words, the driving simulator technique improvement is not the only reason here because environmental and cost issues related to the engine or driving terrain are also pushing factors. Therefore, the CBR CCV did start the research into using the driving simulator for the TBT test again. The start of the pilot was done by analyzing its usage by experts like driving examiners. They reported positive experiences in terms of no problems with simulator sickness. This was the reason for starting the pilot for candidate drivers. The pilot for driver candidates is running during personal communication with the Product Manager CCV at the CBR.

Based on the knowledge about driving simulator usage for the TBT test so far, it is believed that the driving simulator could be used for the TBT test. The TBT test does examine the gazing behavior of drivers and not their traffic participation skills. Therefore, the type of driving simulator used seems suitable to assess the gaze behavior of truck drivers. However, assessing drivers' traffic participation in a driving simulator is something that is not researched in this pilot. The pilot test results finally have to show whether the test scores on the simulator are comparable to the original test scores. Thereby, it is noticed that the simulator test may be experienced as more complex than the test on the road. The argument for that statement is that drivers do drive on the road eventually and not in a simulator. It is also mentioned that this TBT test is particularly suitable for driving simulator usage since there will always be the original driving test afterward. This argument of sequential testing makes it clear that the driver does not pass the actual driving test solely based on driving in a simulator.

The driving simulator used for this pilot is the "Ediser Simu-PL." The simulator is a truck and bus driving simulator for novice and experienced driving license or professional training. It is a compact high-end simulator mounted on a Dynamic Motion Platform (optional) with a physic hardware dashboard, external mirrors, built-in monitor displays, and an accurate eye-tracking system (Simucar, 2020). The simulator is shown in Figure 5.

Figure 5
The Ediser Simu-PL driving simulator, source Simucar (2020)

The experiences with driving simulator usage for the truck driving TBT test show that a high-end driving simulator seems promising to test gaze behavior. The pilot does suggest a possibility for a future method in which there is a combination of a driving simulator test to assess gaze behavior and a follow-up on-road driving as the final overall driving assessment. These results support the other interview research finding that suggests using the driving simulator as an additional element to the on-road driving test and not a replacement.

6. Interpretation & discussions

In this chapter, the research results are interpreted. In paragraph 6.1, an interpretation of the literature research results can be found. Paragraph 6.2 elaborates on the interpretation of the questionnaire. The follow-up interviews are interpreted in paragraph 6.3. The findings of both research methods on hazard perception are interpreted in paragraph 6.4. Finally, the research approach is discussed in paragraph 6.5.

6.1 Interpretation of literature research

The literature research results show an overview of what is known in the literature about driving simulator usage to assess driving performance. The framework shows an overview of the available information that could indicate to what extent driving simulators could be useful regarding transferability, reliability, and validity. The additional value of this literature research is that it combines the various information on driving simulator usage and combines it in a detailed overview for each part of a car-driving test. An overview that has not been explored in preceding research. Thereby, the overview of the available literature information stresses the presence of some contradictions in the literature. Awareness of these contradictions could contribute to future research in identifying the reflected opinions. The rest of this paragraph discusses the most significant contradictions found in the literature research.

6.1.1 Driving simulator development related to specific research purposes

Driving simulator usage is rising because of both technological developments and cost reduction (De Winter (2009); Eryilmaz et al. (2014)). However, a contradiction is found in the literature about this statement. The rise of driving simulators resulted in advanced simulators developed for specific research topics, like the effects on car driving caused by mobile phone usage, alcohol consumption, or mental disorders diseases effects (Frittelli et al., 2009; Leung et al., 2012; Biederman et al., 2012). Based on the literature research, driving performance assessment under ordinary circumstances is not a research topic linked to investigating the potential of driving simulator usage.

The lack of a driving simulator push into specific research directions can be explained by the phenomenon of “essential realism” (Parkes, 2005). The technological development of driving simulators for particular research purposes is based on the commercial interests of these manufacturers (Parkes, 2005). Therefore, the focus should not just be on developing visual views and motion system technology but also on making it straightforward for which it should be used. Essential assessment requirements for the different driving test parts should be considered to create an upswing in using driving simulators for human driving performance assessment related to the on-road car-driving test. In conclusion, the relationship between technological developments and driving simulator usage for particular research purposes is not as straightforward as it seems; it depends on how you define essential realism.

6.1.2 Ambiguous results for particular car-driving test parts

Contradictions were found in the literature for some driving test parts, which led to ambiguous results. For example, different results were found for the driving performance results of driving on straight and curved roads in a driving simulator. Namely, Gemonet et al. (2021) concluded that drivers tend to comply better with speed limits on simulated roads than in the real world. The researchers concluded that simulator drivers seemed to show more consistent driving behavior for this speed limit factor than real road drivers. On the other hand, the research of Blana & Golias (2002) indicated that straight roads with lower speed limits or curved roads with higher speed limits did increase the variability of the lateral road displacement compared to the real world. Therefore the usefulness of the results remains questionable.

Another significant contradiction was found in the validity of driving simulator results for overtaking and side-way movements. Wang et al. (2010) found positive results on relative validity for comparing lateral control and the standard deviation of lane positioning between the simulator and the road. On the other hand, the research of Pan & Shen (2022) indicated that their results of driving on straight and curved roads in a driving simulator could be biased because of different driving circumstances. Biased results from varying circumstances between the environments would indicate negative results on the validity of driving simulator training results.

6.2 Interpretation of questionnaire results

The questionnaire was meant to explore the driving simulator research development in various countries. The questionnaire was spread amongst members of the international organization CIECA. It is essential that the questions were asked to members from different countries worldwide since the traffic situations and rules are different in other countries (Cao et al., 2022). Therefore, the international questionnaire also considers the different driving cultures and perceptions.

The questionnaire results showed that research on driving simulator usage for assessing human driving performance in a driving test is still in its infancy in other countries. Of the 36 members of the international CIECA organization, only three countries did mention that they did have any experience with research in this field. The lack of research in multiple countries these days could be because a new technology requires adaptation time (Ronen & Yair, 2013). Resistance (Lee, 2002) could also be one of the reasons since people could prefer the traditional way of testing and, therefore, would not explore new options that use other technologies to assess driving performance. Both adaptation time and resistance could be explaining factors for countries that did not even start researching the opportunities to use the driving simulator in their driving training and testing program. However, this is an assumption since none of the questioned countries did elaborate on their intrinsic motivations for whether or not to use driving simulators. Other factors like lack of research time, money, or simply not having interest at all could also be an explanation.

6.3 Interpretation of interview results

The interviews were conducted as a follow-up to the questionnaire results. The interviews did result in more detailed information about driving simulator usage and research in the selected countries from the questionnaire: Finland, Estonia, and Sweden. All three countries did report positive experiences with driving simulator training in their education program. Estonia did note that the country uses driving simulators to train and test nighttime driving. The use of driving simulators for nighttime driving is also done in other research (Bella et al., 2014). Finland does make use of driving simulators to train hazard perception. This driving skill is trained in the education program to mainly learn drivers how to cope with slippery roads in icy conditions. Sweden is using driving simulators to train hazard perception as well. Despite the advantages of training with driving simulators they experience, like the accuracy of feedback, restrained driving style, and standardizable teaching software, there is no belief that the driving simulator could replace the traditional driving test on the road according to the three countries. An important counterargument is that driving in a simulator would be hard to compare with driving in the real world. Driving in a simulator was considered as driving in a vacuum instead of driving in a constantly changing environment, as well as an argument written down in the literature (Van Emmerik & Kappé, 2005). Another counterargument was that Finland did notice some drivers suffering from physical symptoms like dizziness and headache, which could be symptoms of simulator sickness. This phenomenon influences the driving style (Talsma et al., 2023).

Despite these counterarguments, findings of ongoing research in Sweden led to new insights into developing a more comprehensive driving test using driving simulators to assess hazard perception. Sweden believes the driving simulator could add value to the car driving program in assessing hazard perception. The interview results, therefore, show a new research direction for follow-up research. Thereby, the interview results also show that information from practice reflects the opinion that the driving simulator is not believed to be a substitute for the car-driving test itself.

6.4 Interpretation of hazard perception in a driving simulator

The information from practice about the additional value of driving simulator usage to assess hazard perception in developing a more comprehensive driving test is promising. Hazard perception is an important driving skill for road safety (Ngueutsa & Kouabenan, 2016). Therefore, results from the literature on hazard perception assessment in driving simulators are highlighted in this paragraph. Two different opinions are found in the literature regarding the additional value of driving simulators in assessing drivers' hazard perception.

The literature research findings on hazard perception show a decreased feeling of being at risk while driving on simulated roads. However, results from the interviews with Finland and Sweden show a contradiction regarding the usefulness of the driving simulator in assessing hazard perception. Both countries believe the simulator is useful for testing drivers' hazard perception in a controlled and safe environment where predefined risky driving scenarios can be repeated (Wynne, Beanland & Salmon, 2019). Therefore, there is a contradiction in interpreting the hazard perception assessment results using a driving simulator. On the one hand, the driving simulator could better assess hazard perception since it is hard to test risky driving situations in the real world, especially multiple times (Hirsch et al., 2016). On the other hand, the hazard perception while driving on simulated roads would not represent the hazard perception needed while driving on actual roads. Drivers in a simulated driving environment would not feel at risk compared to the real road (Blana & Golias, 2002).

However, the importance of hazard perception to road safety has been highlighted. Therefore efforts have been made to the feasibility of hazard perception tests in training and testing novice drivers (Scialfa et al., 2011). Hazard perception is the only driving skill correlated with crash risk (Wetton, Hill & Horswill, 2011; Boufous et al., 2011). The benefits of developing the hazard perception skill have been reported in simulated driving environments and on the road (Scialfa et al., 2011). Despite the importance of the hazard perception skill, the on-road driving test faces difficulties regarding its assessment. For example, the random occurrence of hazards on the real road and the variability in the assessor's driving performance rating (Wetton, Hill & Horswill, 2011) make it challenging to achieve a standardized and acceptable on-road driving test for assessing hazard perception. Although, using driving simulators to assess hazard perception also involves disadvantages compared to the road. However, the advantages of using a driving simulator to assess hazard perception could outweigh disadvantages like lower realism and reduced field of view. This line of reasoning has been chosen for this research to explore to what extent hazard perception assessment could probably be improved. Therefore, this research recommends developing a driving simulator's hazard perception assessment using the new insights from the research framework that combined information from the literature and practice about driving simulator usage.

6.5 Discussion on the research approach

The research approach included both types of information from literature and practice. Combining both types of information shows the different research opinions that could strengthen or outweigh each other. It also shows the potential differences between what is stated in literature and what is experienced in practice. The combination of different types of information resulted in a complete overview of what is known in the particular research field of driving simulator assessment of driving performance.

However, there are some limitations related to the research approach that was chosen. First, the research did not explicitly explore the relationship between the different driving simulator types and their usability for driving performance assessment. This research shows that different simulator types were used for each driving skill and research purpose (paragraphs 4.1 until 4.7). Driving simulators could roughly differ in static- or motion-based and high, medium, or low fidelity levels (paragraph 2.3). Therefore, whether or not a driving simulator could be used for the on-road driving test would require more specific research on a particular driving simulator type that could be used to measure or assess a specific driving skill. There should be detailed follow-up research in combination with particular driving skills to investigate if driving simulator results could be useful regarding transferability, reliability, and validity.

Secondly, since very little research has been carried out about driving simulator usage in assessing driving performance, an explorative research method is used to gather more information (Brooks et al., 2013). This research method provided new insights into a driving simulator regarding whether or not to use it for the assessment of a driving test. However, this type of research could not find concrete information on the usefulness of driving simulator results regarding transferability, reliability, and validity. Experiments are a better tool to test the usefulness of a specific driving simulator type for a particular assessment purpose like a driving skill. Matowicki & Přibyl (2017) researched the validity of driving simulator usage by evaluating other studies on driver performance validity of driving simulators. These studies conducted experiments to investigate driving simulator validity and thus seem to be a useful research tool. Therefore, experimental pilots are most likely needed as follow-up research on investigating the driving simulator transferability, reliability, and validity.

Finally, this research did not address the topic of simulator sickness. Simulator sickness is a motion sickness that could be present in simulations (Helland et al., 2016). It is a significant problem that could occur during driving simulations. Symptoms of driving simulator sickness like dizziness, headache, and visual disturbances were reported by Finland as well. However, this study did not include simulator sickness in the research scope following the reasoning of Mullen et al. (2010). The results of their research showed that drop-outs because of driving simulator sickness turned out to be not the systematically poorest drivers. Their research ensured that driving simulators could assess the performance of drivers needing it the most. Even though this research scope excludes driving simulator sickness, it is a phenomenon that cannot be entirely ignored when implementing driving simulators in the licensing program. Therefore, it is important to consider that simulator sickness depends on the driving simulator type, the particular driving task, and personal characteristics. These factors should be researched when future research suggests a specific driving simulator type for driving performance assessment.

7. Conclusion

Driving simulators allow for assessing human car driving performance in a controlled, safe, and relatively realistic driving environment. However, driving is a complex activity involving many factors. Therefore, this research aimed to answer the following research question: “*To what extent could driving simulators add value to the traditional on-road car-driving test in order to assess human driving performance?”* The findings of the current research support follow-up research in different research directions.

The results showed that using driving simulators could lead to a more comprehensive on-road car-driving test regarding risk perception assessment. According to the results from the literature research, the driving simulator does have some advantages for assessing hazard perception compared to the on-road assessment. Not only could dangerous situations be repeated and tested using different scenarios beforehand, but the divers are actually not exposed to any risk. Therefore, the additional value of the driving simulator can be found in the fact that it is more difficult to test (repeatedly) on a wide range of risky scenarios on the road. A transportable driving simulator without a moving base could be useful according to information from experience with the driving simulator’s risk perception assessment in Sweden. The results of the in-depth interviews with Finland and Sweden support the findings in the literature. Finland and Sweden argue that the driving simulator could complement the practical driving test. However, at the same time, they argue that the driving simulator should never completely replace the test on the real road since there are too many differences to face.

This research also shows promising results for assessing human driving performance while performing “overtaking & side-way” movements on a driving simulator. This part of the driving test seems interesting for further research since the study results indicate that driving simulators could be used regarding their human car driving performance assessment results regarding transferability, reliability, and validity. According to findings from the literature research, a fixed-base driving simulator with a blind spot could be appropriate.

In conclusion, this research shows promising results for the driving simulator’s additional value to the on-road car-driving test in assessing hazard perception and “overtaking & side-way” movements. The results show that simulator-based assessment may be practical, depending on the specific driving task and the type of simulator. However, the study showed that there is still a significant knowledge gap in the driving simulator assessment of the required sets of driving skills for the seven different driving test parts of the Dutch car-driving test that could not be solved by this research alone. Even though follow-up research is needed to close the knowledge gap, one should remember that driving simulator assessment may be effective in the future depending on the specific driving task and type of simulator needed.

8. Recommendations

This chapter provides practical recommendations about how the driving simulator could add value to the assessment of driving performance. Thereby, recommendations for future research are provided. In paragraph 8.1, combinations of driving test parts and specific driving simulator types are recommended to dive deeper into in follow-up research. Paragraph 8.2 emphasizes the importance of using these results to conduct follow-up research for novice and experienced drivers. Additionally, follow-up research should focus on the fact that getting familiar with the driving simulator is necessary to successfully use them in driving licensing programs.

A recommendation to conduct a valid driving simulator pre-test is elaborated on in paragraph 8.4 to follow up on the research finding that driving simulator usage has some promising advantages compared to the on-road testing in assessing hazard perception.

Since the road infrastructure is ever-changing, the last paragraph considers the current developments of introducing automated vehicles to the roads. It combines this development with follow-up research on the potential of the driving simulator to assess hazard perception.

8.1 Driving simulator-type-specific research

This research shows what is already known about driving simulator usage to assess driving performance when taking a driving test. The findings in literature and practice indicate that the available information originated from specific research on measuring certain driving skills. The findings of this research are considered a start of exploration on driving simulator usage to assess human car driving performance. Based on the research results, further research should be developed on exploring the following combinations of driving simulator types and specific parts of the on-road car-driving test in the Netherlands:

- Start of the car-driving test – a fixed-base high-fidelity driving simulator
- Curved and straight roads – at least medium-high fidelity fixed-base driving simulator
- Driving at intersections – high fidelity driving simulator
- Merge and exit on the highway – no concrete findings on the simulator type
- Overtaking and side-way movements – a fixed-base driving simulator with blind spot
- Special road intersections – no concrete results on driving simulator type
- Special road maneuvers – no concrete findings on driving simulator type

Based on what information was gathered from the literature and practice, a rating scale is made to classify to what extent these specific driving simulator types could be used to assess certain parts of the car-driving test. Table 26 shows the three-step classification with an additional explanation based on information found during the research, which can be found in Tables 6 to 12. The classification is “Low-Medium-High,” in which a “low” classification means that the particular driving simulator is not really recommended for follow-up research, and a "high" classification means it is worth conducting follow-up research for this driving simulator type in terms of assessing the particular driving skills belonging to the driving test part.

Table 26

Driving simulator-type specific recommendations for driving performance assessment of the different car-driving test parts

Driving test part	**Recommendation for follow-up research**	**Driving simulator characteristics information from the research**
Start of the car-driving test	Fixed-base high-fidelity driving simulator: ***Medium***	• Widening the field of view has a significant effect on speed and lane change validity • Insufficient display resolution can decrease the visual fidelity of the simulator • Improve display resolution has no significant effect • To be able to assess primary task performance, fixed base driving simulation is recommended • Speed variability is significantly lower in "out-car" set-up • Glance in rear mirrors significantly higher "in-car" set-up
Curved and straight roads	Fixed-base Medium-High fidelity driving simulator: ***Low***	• The horizontal field of view in a simulator positively correlates with driving performance in terms of speed choice and lateral position • In fixed-based driving simulators, there is no feeling of acceleration (longitudinal and lateral), and therefore no feedback is present to correct the speed, especially during driving corners; there is a lack of speed correction • There is a need to distinguish between driving performance on straight and curved roads • For straight roads, it is essential to have vibration feedback and the sound of the engine that influence the braking force • The demand of the driving task needs to be at least moderate for all visual attention measures to be comparable between the simulator (high fidelity in this research) and the real road • There are limitations to assessing driving behavior in a mid-level fixed-base driving simulator
Driving at intersections	High-fidelity driving simulator: ***Medium***	• Driver's behavior at intersections needs to be investigated in a realistic simulator environment to generalize the behavior to real road driving • Factors that influence the braking initiation are the turning direction, horizontal viewing angle, and motion simulation • A low-fidelity simulator is not suitable for reproducing valid braking behavior • There is evidence that a high-fidelity simulator is valid regarding the visual attention of drivers at intersections
Merge and exit on the highway	No concrete findings on the simulator type	• Not applicable
Overtaking and side-way movements	Fixed-base driving simulator with blind spot: ***High***	• Having a blind spot is essential when performing a left lane change maneuver • Most driving simulators do have both a front and rear view; having a blind spot includes a side view as well • A fixed-base driving simulator was used to examine the driving performance, and it provided continuous data on longitudinal and lateral speed, acceleration, and lane position
Special road intersections	No concrete findings on the simulator type	• Not applicable
Special road maneuvers	No concrete findings on the simulator type	• Not applicable

It is essential to notice that this research could not give an unambiguous answer to what driving simulator type fits a specific driving test part the best. Therefore, diving deeper into promising research findings on particular driving skills and driving simulator types is recommended.

8.2 Conduct follow-up research for novice and experienced drivers

This research focused only on driving simulator assessment of novice drivers' performance. However, the research findings could also be used for follow-up research on assessing experienced drivers' skills. The driving simulator has shown its promising contribution to road safety in other research with experienced drivers, such as Dotzauer et al. (2013) and Lee et al. (2003). Another example of driving simulator usage to assess the driving performance of older and experienced drivers is the research of Piersma (2018). The research concluded that driving simulator rides can add value to the fitness-to-car-driving assessment of patients with Alzheimer's disease. The research investigated the new strategy of using the combination of clinical interviews, neuropsychological tests, and driving simulator rides to assess the fitness to drive of older driving patients with Alzheimer's disease. The conclusion was that in over 90% of the patients, the driving simulator rides helped to determine whether these patients would pass the official on-road driving test. Piersma's (2018) research clearly shows the promising effect of driving simulator usage to assess the driving performance of experienced drivers and its potential effect to improve road safety.

The current research, together with the research of Dotzauer et al. (2013), Lee et al. (2003), and Piersma (2018), are examples of how a driving simulator could provide insights into the interaction between human, vehicle, and road characteristics that could influence the road safety (Boyle and Lee, 2010). The diversity of driving simulator usage shows indications of the promising effect of driving simulators on road safety. Future challenges and opportunities could be expected for driving research in terms of naturalistic studies identifying crash data and simulator studies providing insights into underlying mechanisms like glance patterns (Boyle and Lee, 2010). Therefore, these research findings should not only be used for novice drivers representing only a particular part of the road users.

8.3 Familiarity with driving in a simulator

Regarding the driving behavior that a subject could show in a driving simulator, getting the subject familiar with driving in a simulator would be recommended. The research results, based on the expertise of Sweden on driving simulator usage, show that drivers must get used to the driving simulator before an actual test on a driving simulator starts. The importance of getting used to the driving simulator equipment and its virtual driving environment is argued in multiple types of research (Gemonet et al., 2021; Meuleners & Fraser, 2015; Ronen & Yair, 2013).

8.4 A more comprehensive driving test

The results from the literature research and in-depth interviews with Finland and Sweden showed promising findings on driving simulator usage to assess hazard perception. Although the practice results were only based on driving simulator training results so far, there are indications from research started in Sweden that the driving simulator could be used as a pre-test to assess drivers' hazard perception before they may start the on-road driving test. It is believed that the driving simulator could be a good complement to the on-road driving test in terms of hazard perception, and its usage could result in a more comprehensive driving test. Based on these research results, follow-up research is recommended to be conducted on developing a valid driving simulator pre-test that could be useful to assess the hazard perception to conduct a more comprehensive car-driving test.

Since hazard perception is the only driving skill correlated with crash risk (Wetton, Hill & Horswill, 2011; Boufous et al., 2011), countries like Australia and the UK introduced a Hazard Perception Test. The test uses a driving simulator to assess whether drivers can timely perceive and predict potential hazards (SWOV, 2019). Results from Queensland (Australia) show a lower crash risk for candidates who passed the HPT compared to the drivers who did not (SWOV, 2019). Thereby, a driving simulator-based hazard perception test is safer than on-road testing of hazard perception because traffic hazards can be reliably recreated without exposing the drivers to danger (source Cao et al., 2022). Therefore, it is recommended to build on the practical information from the Swedish research and take follow-up research steps towards developing a valid hazard perception test that could be appropriate to use as a pre-test for the Dutch car-driving test as well. This paragraph elaborates on recommendations for important factors to develop a valid hazard perception test.

Developing a driving simulator's hazard perception pre-test does require the fulfillment of specific criteria. Since hazard perception skills depend on experience and age (Scialfa et al., 2011; Chan et al., 2010), the test should be able to distinguish drivers from these different groups. Regarding the fulfillment of this criterium and facing the difficulties in achieving a standardization for hazard perception assessment, there are five principles proposed by Wetton, Hill & Horswill (2011) to develop an effective driving simulator-based hazard perception test. It is recommended to consider these principles when follow-up research is conducted on this research topic.

1. A hazard perception test should only measure the hazard perception skill and not the risk-taking propensity
2. The hazard perception test should be able to differentiate between people based on their particular levels of hazard perception skill and not based on response time differences
3. Hazard scenarios should be un-staged, not deliberately creating dangerous situations and avoiding unrealistic stimuli
4. The wording of the instructions of the test should unambiguously define what situations ask for a response in terms of safe driving
5. The test should be able to identify people who are trying to cheat the test

Introducing a simulator-based hazard perception pre-test for the on-road car-driving test includes evaluating driving performance scores. Therefore, profiling the driver behavior of drivers is required. Regarding the focus on the hazard perception driving skill, the following set of driving performance indicators could be used for profiling safe and unsafe drivers (Trontelj et al., 2017):

- Speed violation
- Lane deviation
- Acceleration exceeding
- Safety distance violation

It would be recommended to develop different driving scenario's in the driving simulator to assess these indicator variables (Trontelj et al., 2017). For example, the driving scenario focuses on the technical road properties only like different speed limits and roads with different curve radii, or the driving scenario focuses on varying the traffic intensity to test the distance to the leading vehicle. Based on the outcomes of these indicator variables for different driving scenario's tested in the driving simulator, a qualitative safety score could be used for safe driving behavior profiling (Trontelj et al., 2017). The outcomes of the safety profiling could indicate whether or not a driver can drive safely on the road based on his hazard perception.

In conclusion, follow-up research on developing a valid driving simulator-based pre-test for hazard perception assessment includes various research factors. Although a lot still has to be figured out for developing this driving simulator pre-test, the research findings regarding the driving simulator's hazard perception assessment are promising. Therefore it is recommended to develop follow-up research on this topic.

8.5 Engage simulator-based driving scenarios with automated vehicle developments

In terms of deploying automated vehicles (AVs), introducing driving scenarios that include these Avs would be recommended in the future. These AVs are expected to improve flow efficiency and safety. However, their deployment on motorways would influence the traffic environment (Schoenmakers, Yang & Farah, 2021). Introducing the Avs requires behavioral adaptation to the changing road infrastructure, and driving simulators have been proven to be a suitable solution for testing how driving behavior will be influenced (Schoenmakers, Yang & Farah, 2021). Since the interaction between AVs and other human-driven vehicles is not extensively researched (Schoenmakers, Yang & Farah, 2021), introducing a driving simulator-based hazard perception pre-test could add value to this research area. Namely, when follow-up research is developed to conduct a valid driving simulator-based pre-test, driving scenarios could be included to test the risk perception for driving environments with and without AVs. Therefore, setting up the driving simulator-based pre-test for hazard perception assessment could create opportunities to increase the amount of research on the interaction between AVs and other human-driven vehicles when the AVs development is taken into account in the driving simulator scenarios.

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Appendix A. Informed consent

You are invited to participate in a research study titled "Exploiting the opportunities of taking a car-driving test on simulators." This study is being done by Doris van Opstal from the TU Delft in association with internship provider CBR (*Centraal Bureau Rijvaardigheidsbewijzen*).
The purpose of this research study is to gather information about experiences with driving simulator usage for driving training and testing, and will take you approximately 10 minutes to complete. The data will be used for the following:

- A practical data inventory about the experiences with driving simulators.
- Filling in the gaps in the literature about the usefulness of driving simulators instead of real-world driving.
- Providing this master thesis research with sufficient information, together with the information from the literature, is fundamental research for more follow-up studies concerning the implementation of the driving simulator in the examination program.

We will ask you to answer some questions about your experience with (driving) simulators as a tool for training or examining driving skills. Additionally, contact information will be asked for possible follow-up interviews based on the questionnaire results.
As with any online activity, the risk of a breach is always possible. To the best of our ability, your answers in this study will remain confidential. We will minimize any risks by storing the data in a particular way. The questions are being asked via a standardized format used by CIECA. Therefore, the data will be stored by CIECA. The responses are sent via e-mail to the researcher, who will store the data on OneDrive. The questions and data will be deleted after the information-gathering period. Thereby, IP addresses are not collected. The contact information that is asked from you is meant for follow-up questions about the research topic. There will be no questions concerning personal confidential information.
Your participation in this study is entirely voluntary, **and you can withdraw at any time**. You are free to omit any questions.
Researcher: Doris van Opstal
Affiliation: the Delft University of Technology, the Netherlands
Contact: D.P.E.vanOpstal@student.tudelft.nl
+31 6 83 250 705

Appendix B. Questionnaire

B1. Questionnaire set-up

The questionnaire set-up starts with the opening statement introducing the research topic and its context. This opening statement is shown in Appendix A. After the introduction, Table 27 asks the audience to read and affirm the explicit consent points about participation risks and privacy issues. Then, five crucial terms are explained to the participants beforehand to prevent misunderstandings of the questions. Reliability, transferability, validity, driving performance, and driving skills are the essential phrases here, which are explained in paragraph 1.4. After the participants have read these definitions, they can start the questionnaire.

Table 27

Explicit consent points about participation risks and privacy issues

PLEASE TICK THE APPROPRIATE BOXES	Yes	No
A: GENERAL AGREEMENT – RESEARCH GOALS, PARTICIPANT TASKS, AND VOLUNTARY PARTICIPATION		
1. I consent voluntarily to participate in this study and understand that I can refuse to answer questions. I can withdraw from the study at any time without having to give a reason.	☐	☐
2. I understand that taking part in the study involves:	☐	☐
• *The information is captured by completing the online questions about your experience with driving simulators.* • *All members of CIECA are being asked to be a participant in this research* • *A possible follow-up online interview could include audio recordings* • *The audio recordings will be transcribed as text and destroyed when the thesis report writing is finished*		
B: POTENTIAL RISKS OF PARTICIPATING (INCLUDING DATA PROTECTION)		
3. I understand that taking part in the study also involves collecting specific personally identifiable information (PII) and associated personally identifiable research data (PIRD) with the potential risk of my identity being revealed.	☐	☐
• *Please list which PII and/or PIRD will be collected and summarise (if) any potential risks of re-identification (e.g., public/professional reputation)* • *If you agree to fill in your contact information, personally identifiable information like your name/ phone number/ e-mail is shared with the main research team only* • *Your personally identifiable information will be de-identified if any of it is used in the thesis report and further research*		
4. I understand that personal information collected about me that can identify me, such as [*e.g., my name or in which country you work*], will not be shared beyond the study team.	☐	☐
5. I understand that the (identifiable) personal data I provide will be destroyed	☐	☐
• *The data will be destroyed after the analysis of the results from the online interview questions* • *The re-identification of the results will be the results shown in the thesis report*		
C: RESEARCH PUBLICATION, DISSEMINATION, AND APPLICATION		
6. I understand that after the research study, the de-identified information I provide will be used for	☐	☐
• *If relevant, these quotes will refer to a de-identified source, and no personal information is shared here.* • *The conclusions of the thesis report* • *As an information source for recommendations meant for follow-up studies*		
7. I agree that my responses, views, or other input can be quoted anonymously in research outputs	☐	☐
D: (LONG-TERM) DATA STORAGE, ACCESS, AND REUSE		
8. I give permission for the de-identified experience data about driving simulator usage during training or examining that I provide to be archived in the TU Delft education repository so it can be used for future research and learning.	☐	☐

B2. Questions

The list of questions that were asked to CIECA members is shown below. The questions were meant to get insights into whether or not research on driving simulator usability for driving tests has been conducted in these countries.

1. Are you aware of any research on the use of driving simulators? This may refer to any vehicle category. (If no: go to „Remarks" and exit)
2. Is the research related to measuring driving skill performance in training/testing, or has it been conducted for other purposes?
2. a) If related to measuring the performance of driving skills in training/testing, which driving skills does the research cover?
3. Are you aware of any research on driver training conducted on a simulator? (If no: skip sub-questions a, b, c).
3. a) Are the training results reliable?
3. b) Are the training results transferable?
3. c) Are the training results valid?
4. Are you aware of any research on a practical driving test conducted on a simulator? (If no: go to „Remarks" and exit)

4) a) Are the test results reliable?
4) b) Are the test results transferable?
4) c) Are the test results valid?
5) Would you be available for a possible face-to-face/phone interview?
6) If yes, please provide contact information (e-mail address, phone number)
7) Additional remarks?