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Physical Infrastructure Needs for Autonomous & Connected Trucks

An Exploratory Study

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Preface

This master's thesis is the final work of the Master of Science education at the Department of Civil and Environmental Engineering at the Norwegian University of Science and Technology (NTNU). The thesis is written during the spring of 2018 in Trondheim, Norway, where it constitutes 30 points within the study program.

The goal of this master's thesis has been to examine the impact of future autonomous trucks and truck platoons on the Norwegian road design and physical infrastructure, as an improved road design can enhance these vehicles benefits and save resources during construction. The thesis is part of a project conducted by the Norwegian Public Road Administration evolving around updating the design handbooks. Together with the master's thesis, a scientific paper was written; *Physical Infrastructure Needs for Autonomous and Connected Trucks: An Exploratory Study*. This was submitted and accepted by the 2018 European Transport Conference.

A big thanks to my supervisor Kelly Pitera, Associate Professor at the department of Civil and Environmental Engineering, NTNU. She gave continuous advice and great support throughout this period. Also collaborated and contributed greatly on the scientific paper.

Thanks to Ane Storsæter and the rest of the Norwegian Public Road Administration for contributing and helping out with the interviews, giving a scholarship, and granting information regarding their Intelligent Transportation Systems project on E8 in Troms. Special thanks to my future employer, ÅF Engineering, for contributing with technical drawings of E6, and to everyone who helped proofreading or contributed in any other way to this thesis.

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Sammendrag

Den raske utviklingen av selvkjørende kjøretøy har lagt grunnlaget for selvkjørende lastebiler og konsepter som platooning med lastebiler. Disse teknologiene kan potensielt bidra til å minimere de store problemene med transport på veg, som antall drepte, energibruk, og trafikkflyt. Det er forventet at mellom 2016 og 2050 vil transport av gods på norske veger øke med nesten 100 %, og med landets spredte populasjon, kystlinje og fjell, er det veldig få høykvalitets 4-felts motorveger, hvor disse konseptene tidligere har blitt testet. Sammen med lite litteratur om deres fremtidige betydning på infrastrukturen, er det vanskelig å si hvordan selvkjørende lastebiler og platooning vil fungere i Norge, og hva som eventuelt må til for å gjøre vegene brukbare for dette formålet.

Med det overliggende målet om å undersøke hvordan vegens design kan bli berørt av bruken av selvkjørende lastebiler i 2050, utforsker denne oppgaven fremtiden til automatiske lastebiler gjennom de følgende forskningsspørsmålene:

1. Hva er forskjellen i kjøretøyegenskaper mellom konvensjonelle og selvkjørende lastebiler?
2. Hvilke elementer av vegens design blir påvirket av selvkjørende lastebiler og/eller lastebil platooning?
3. Hvordan kan disse elementene blir forbedret slik at de støtter selvkjørende lastebiler og lastebil platooning?

Denne utforskende studien bruker eksiterende litteratur, eksperter og norske vegstandarder gjennom kvalitative forskningsmetoder som litteratursøk, intervju, og dokumentanalyse. Siden de nødvendige teknologiene og konseptene er relativt nye, er det svært lite litteratur, og enda mindre kvantitative data. Prosedyren tok i bruk eksisterende litteratur for å skaffe nok kunnskap og forståelse for temaet til å lage en basis for analyse og videre diskusjoner om fremtidig fysisk infrastruktur, med det følgende resultatet som en pekepinn mot hvilke områder som sannsynligvis blir berørt og vil trenge videre forskning.

Resultatene viser at førstegenerasjons selvkjørende lastebiler bare vil ta vekk risikotakeren (sjåfører), noe som vil bidra til en annen oppførsel i trafikken. Senere generasjoner vil forbedre andre kjøretøyegenskaper, inkludert reaksjonstid. Disse forandringene vil minimere minimumskravene til de fleste værparameterne, med stoppsikt og vertikal kurvatur som de mest forbedrede (75 og 51 %). Men, det er den nye oppførselen til kjøretøyene som åpner de største mulighetene, siden det gir en større fleksibilitet enn hva som har funnet sted i vegdesign før. Retningslinjer for å lede sjåfører eller for å holde dem våkne trengs ikke lenger, og andre faktorer som tid, miljø eller økonomi kan derfor bli bestemmende for designet.

Flere av vegens elementer vil sannsynligvis bli påvirket av lastebil platooning, på grunn av deres lengde, annen lastmekanikk og høyere vekt. Bruer vil muligens trenge forsterkninger, det

samme gjelder rekkverk. Andre strukturelle elementer, inkludert asfalt, vil sannsynlig også trenge forandringer, men felles for alle er at det ikke har vært nok forskning på disse elementene. Forbikjøringsfiler blir også påvirket av platooning, siden forbikjøringsdistansen av en platoon med to lastebiler er 160 % lengre enn dagens dimensjonerende lastebil. Tunneler og kryss vil sannsynligvis se forbedringer ved bruk av digital infrastruktur, som tilkoblede kjøretøy, med bare minimale endringer av den fysiske infrastrukturen. Presisjonskjøring vil kunne gjøre kjørefelt smalere, som enten vil redusere det totale tverrsnittet eller, i tilfellet en 4-felts veg, lage nok ekstra plass til et femte felt.

Denne oppgaven inkluderer en vitenskapelig artikkel, som ble akseptert av 2018 European Transport Conference.

Summary

The rapid development of autonomous vehicles has spawned autonomous trucks and concepts such as truck platoons. These technologies can potentially contribute to lower several key issues regarding road transportation, like number of fatalities, energy consumption and traffic flow. Between 2016 and 2050, transportation of goods on roads in Norway are expected to increase by nearly 100 %, and with the country's spread population, coastline and mountains, very few roads are high-quality 4-lane highways, where these concepts have had a few limited real-life tests. Together with scarce literature on infrastructure impacts, it is difficult to state how autonomous trucks and truck platoons will function in Norway and what potentially must be done to make roads supportive.

With the overall goal of examining how road design will be affected by the use of autonomous trucks in 2050, this thesis explores the future of truck automation through the following research questions:

1. What is the differences in vehicle characteristics for conventional trucks vs autonomous trucks?
2. What elements of road design are impacted by autonomous trucks and/or truck platoons?
3. How can these elements be improved to be supportive of autonomous trucks and truck platoons?

This exploratory study takes use of existing literature, experts and Norwegian road design handbooks through the qualitative methods of literature review, interview and document analysis. As the necessary technologies and concepts are relative new, the amount of literature is low, with quantitative data even more scarce. The procedure took use of the existing literature to gain knowledge and understanding to create a basis for analysis and discussions regarding the future physical infrastructure, with the findings pointing towards what areas that are likely to be impacted and in need of further research.

The results found first-generation autonomous trucks to only remove the risk-taker (the driver), creating a different driving behavior. Later generations will improve on other vehicles characteristics, including the reaction time. These changes decrease the minimum requirements of most design parameters, with stopping sight distance and vertical curvature seeing the biggest improvements (75 and 51 %). It is however, the driving behavior that creates the biggest possibilities for road design, as it creates a flexibility that has not been seen in road design before. Guidelines to lead human drivers or to keep them alert, are no longer needed, and therefore can factors such as travel time, environmental or economics be decisive.

Several road elements are likely to be impacted of truck platoons, due to their long length, different load dynamics and higher weight. Bridges might require reinforcements, the same

goes for railings. Other structural elements, including pavements, are likely to see changes as well, but there has not been enough research conducted for any of these elements. Overtaking lanes are also influenced by truck platoons, as the overtaking distances of a two-truck platoon increases by 160 % compared to a 22-meter long reference truck, in a worst-case scenario. Tunnels and junctions are likely to see benefits of the digital infrastructure and its corresponding connective technologies, with only minimal adjustments to the physical infrastructure. Precision driving will allow lanes to be narrower than ever before, either reducing the cross-sectional space needed for a road, or in the case of a 4-lane highway, creates enough space for a fifth lane.

Included in this master thesis is a scientific paper, accepted by the 2018 European Transport Conference.

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1 Introduction

Current advances in vehicle technologies attempt to address the large contribution of automotive transport to several key issues, including fatalities, energy consumption, greenhouse gas emissions and traffic congestion. With research and testing of connected and autonomous vehicles (AV), public discussions, successful demonstrations of the technologies, and promises of considerable benefits have ensured a high anticipation of these vehicle innovations.

Transport of goods on roads have been specifically targeted by truck manufacturers and decision-making authorities as an industry which can become more efficient and sustainable. Heavy vehicles have a significant role in contributing to the key issues, through high usage of infrastructure and bad emissions and energy demand characteristics. In Norway, heavy-duty transport contributes about one tenths of all CO_2 released (Ssb.no, 2017) and it is expected that road transport will double through 2016-2050 (Hovi et al., 2017). At the same time, a truck driver shortage is starting to emerge, creating issues due to higher transport prices (Long, 2018).

Autonomous trucks (AT), and in extension, truck platoons (TP), are viewed as feasible within the trucking industry due to their expected benefits. Aligning trucks into a homogeneous group with reduced distance between each member-vehicle, bound together via electronic data communication, allows for a reduction in air resistance (which reduces energy demand) and necessary road space (Ellwanger and Wohlfarth, 2017). But, concerns have been raised by vehicle manufacturers, through Huggins et al. (2017)'s report, on how certain infrastructure elements will limit their ATs and AVs.

This thesis assesses the influence of ATs and TPs on the physical infrastructure, including geometric alignment and specific road elements. Digital infrastructure, road certification and new solutions are also discussed due to their close correlation to how future roads can be designed. The objective of this research is:

How will the road design be affected by the use of autonomous and connected trucks in 2050?

This chapter will explain the background for the thesis, including how ATs and TPs work, and some of its definitions, and the second and third section will introduce the research scope and objective, stating the research questions.

1.1 Background

This section explains background information on AVs, ATs and TPs and why it is being researched so heavily right now. It will also briefly explain the concepts and technology issues and introduce some more important topics like road infrastructure.

It is important to note that AV are used as a general description of all vehicles with automated driving, including cars and trucks. As ATs use the exact same technology as cars, AVs will sometimes be used when the topic includes all vehicles, even though this thesis concentrates on trucks.

1.1.1 Current State of AVs and the Legislation Issue

Numerous manufacturers are currently researching, testing and advancing AV technology. ATs are viewed as important by manufacturers, and in Europe, all the big original equipment manufacturers (OEM) are developing ATs and TPs. Daimler Trucks, Volvo Trucks, Scania and MAN, all took part in the European Commission funded European Truck Platooning Challenge 2016 (ETPC). This section explains the current state of legislation and AVs in different parts of the world and is based on Bishop et al. (2015)'s report.

Legislations for AVs vary in different European countries, but for the countries with big vehicles manufacturers they are usually allowed testing on public roads, including the UK, Germany, Sweden and France. Dutch and Swiss governments have also accepted proposals or allowed testing of AVs, as these countries are big on the research in the field. As these industries are important, authorities want to keep the test programs of national companies within the country's borders, acting fast to allow for testing whenever these big companies (i.e. Mercedes, Volkswagen, Renault, Volvo, Jaguar and many more) ask for a permits or policy changes (Self-driving-future.com, 2016). The European Commission sees big opportunities and has funded numerous projects and research objectives through its Horizon 2020, Workplan 2014-15 for Transport, in which they state that they will "support a gradual progress towards full automation". The opportunities reach far outside the vehicles, with billions of euros in revenue for different developing sectors like software and hardware. They are therefore heavily pushing countries to allow for testing and help funding the research, as it can give an economical boost to the industry (Bonneau and Yi, 2017). This report, as well as many other researchers, points out that the standardization and improvement of regulations is needed, as well as consideration of areas of privacy and data security, perception, accountability and liability.

All European countries are obligated to follow the Vienna Convention (Bishop et al., 2015), in which its road traffic section states several roadblocks to AV operations, including that every moving vehicle must have a driver and that the driver shall minimize his activities other than driving. The ECE Regulation 79 is a regulation in UN Economic Commission for Europe that states automated steering above 10 km/h is not allowed, which also contributes to the difficulty of testing AVs on public roads (UN Vehicle Regulations, 2005). The countries that are mentioned above, have all discarded, changed or added policies to overcome the issues with the rules set by the Vienna convention or ECE Regulation, making it possible for them to allow testing on public roads.

One of the problems regarding new regulations, are that the technology and the impact of the technology, is not deemed safe enough yet. More research is needed to show good safety results. For the ETPC 2016, several measures had to be addressed to be allow the implementation of the challenge, including blinking warning lights and opening the platoon (i.e. increasing the distance between trucks) at certain road elements, such as bridges.

In the US, as with the rest of the world, safety concerns and unknown impacts are main causes as to why legislations for AV testing on public roads are challenging to implement. Demonstrations of technology are viewed as essential by many manufacturers and researchers, this to encourage cooperation between all parties, including suppliers, insurance companies, commercial fleets, stakeholders and regulators. The National Highway Traffic Safety Administration (NHTSA) have also issued a statement with recommendations for legislation of AV testing and information about AV technology to states in an effort to help them to implement AVs safely. Several states have since passed laws on AVs, making it easier for researcher to test and explore technologies, as well as creating jobs (Hayeri et al., 2015).

The Japanese government has also conducted large research projects, mainly on automated driving and truck platooning. Public road testing of AVs have been conducted since 2013 (Bishop et al., 2015).

1.1.2 Autonomous Trucks and Truck Platoons

Often mistaken by the press, connected vehicles and autonomous vehicles are two different technologies. These terms are often seen together, as in a technological aspect they benefit greatly from each other, but they stand for two completely different technologies. Connected vehicles (CV) are able to communicate with other vehicles (V2V), to the infrastructure (V2I), and with other entities such as the Internet (i.e. the cloud) or pedestrians (V2X). Dedicated Short Range Communication (DSRC) or cellular are the two most common ways to send and receive data about traffic conditions, weather conditions, signal phasing and timing, vehicle characteristics, parking information and so on (Lin and Wang, 2013).

Autonomous or automated vehicles (AV) do not need that communication between vehicles, infrastructure or others to function. The technology is designed with sensors to be capable of sensing the surrounding environment and from that; controlling the vehicle by itself. Normally used sensors include ultrasonic sensors, which are short range sound waves, mainly used for automated parking. Image sensors work as the human eyes, and can detect and read signs, traffic signals, markings, and more. Radio Detection and Ranging (RADAR) is used in the same way as on ships and planes with electromagnetic waves detect objects’ speed and range. A laser sensor called Light Detection and Ranging (LIDAR) scan the environment and creates a 3D image, used to track distances and objects. These are the most common sensors, and what is expected to be used in the future (2025ad.com, 2017). This system, which contains many different sensors, is how the vehicles see the world, and is therefore the most important part of an AV. This technology will be expanded on in section 2.1.

For AVs there are two other words that are also often misused, self-driving and driverless. Driverless is when a vehicle is completely free of human input except of destination, these vehicles will allow passengers to do anything else but driving, what is often called *hands-off and eyes-off*. A self-driving vehicle is a vehicle of driving itself unrelated on what level of complexity this is, it could be both automated parking or highway driving. Driverless will be the highest level of a self-driving vehicle. The levels of automation is described by SAE International in their J3016 standard as follows (SAE International, 2014):

- *Level 0: No Automation* assumes full-time control by a driver, even if enhanced by warning or intervention systems.
- *Level 1: Driver Assistance* assumes a driver is in full control of the vehicle, but with assistance of either speed or steering in certain conditions (e.g. Cruise Control or emergency braking).
- *Level 2: Partial Automation* assumes that the system can take control of both acceleration and steering in certain conditions, but with a driver ready to take over and still monitoring the environment (e.g. automated driving during low speed queues or automated parking).
- *Level 3: Conditional Automation* lets the vehicle monitor the environment while controlling speed and steering, but this will only work under certain conditions and with a human as a fallback system (i.e. backup). First level with "eyes off", meaning the human will not have to monitor the environment.
- *Level 4: High Automation* lets the vehicle control everything, with the vehicle also taking over the fallback performance. Under certain difficult conditions a driver must take over.
- *Level 5: Full Automation* assumes the technology is controlling all aspects of the driving performance, and the vehicle is now completely driverless with the passengers free to do as they please. The vehicle must be capable of driving itself in all conditions.

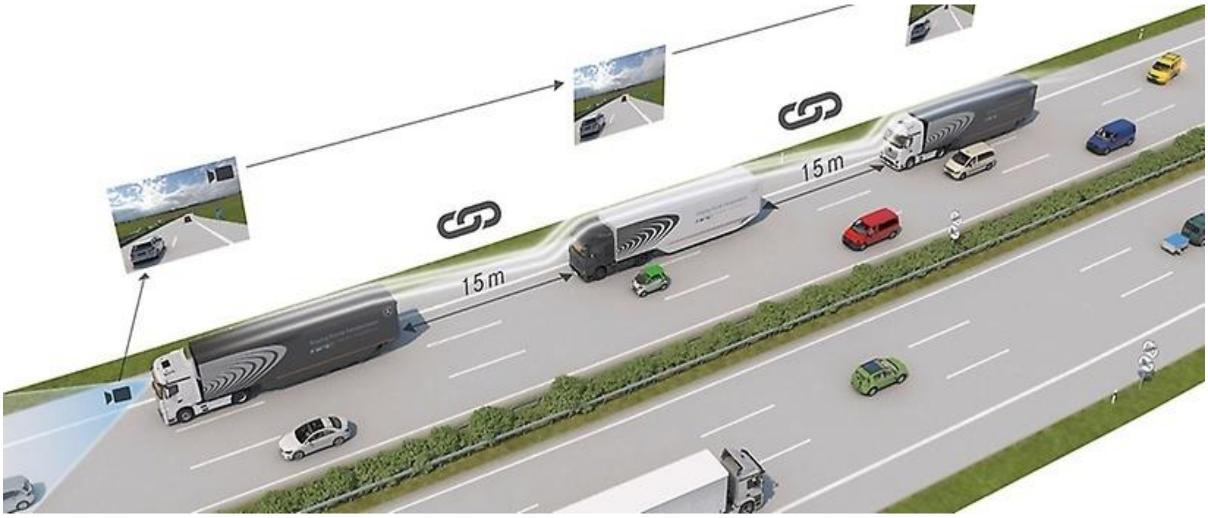

Figure 1. Daimler's truck platoon from the 2016 ETPC (Carsify.my, 2017)

ATs work in the same way as every AV, with the same sensors and systems. Connected and automated vehicles merge the two technologies together and will benefit from the extra information given by other vehicles, road side installations and "the cloud" (Costello and Suarez, 2015). This is also a necessity for the concept of truck platooning, as this needs trucks to communicate with each other (V2V). A platoon of trucks consists of two or more trucks driving very closely behind each other, see figure 1. This is possible due to the automated and connected technologies, which allow the trucks to safely follow each other at as small distances, for example 6,7 meters at 80 km/h (Janssen et al., 2015). The wireless communication between the trucks (often DSRC) allow the lead truck to control the following trucks, both steering and acceleration. Because of the fast communication between the vehicles, they will essentially break at the same time, called *Connected Braking*. Figure 2 compare this breaking technology of a TP with a normal driving situation and with Adaptive Cruise Control breaking.

To ensure safety, all trucks in a platoon are equipped with autonomous sensors, enabling them to act individually if circumstances dictates it. The concept promises easier and more optimized workloads for drivers, better asset optimization and therefore the chance of earning more profit for carriers (Janssen et al., 2015). These benefits have not yet been confirmed, as the technology is too new and not enough testing have been conducted. Most research have been examining fuel savings and improvements of the technology. Testing on public roads have not been very common and without a high enough penetration of ATs with matured technology, the full beneficial gain has not yet been found (Bishop et al., 2015). More tests on public roads are necessary, but restrictions in form of policies and laws are big barriers, as authorities are unsure of the current safety of TPs, and AVs in general. Because of this, Janssen et al. (2015) have suggested a careful introduction of platoons on public roads. A big implementation could have a negative effect on acceptance, and then push authorities to withdraw their policies allowing platoons to drive on public roads. The report suggests starting with a few two vehicle-TPs, as road users need to get familiar with the concept of trains on the road.

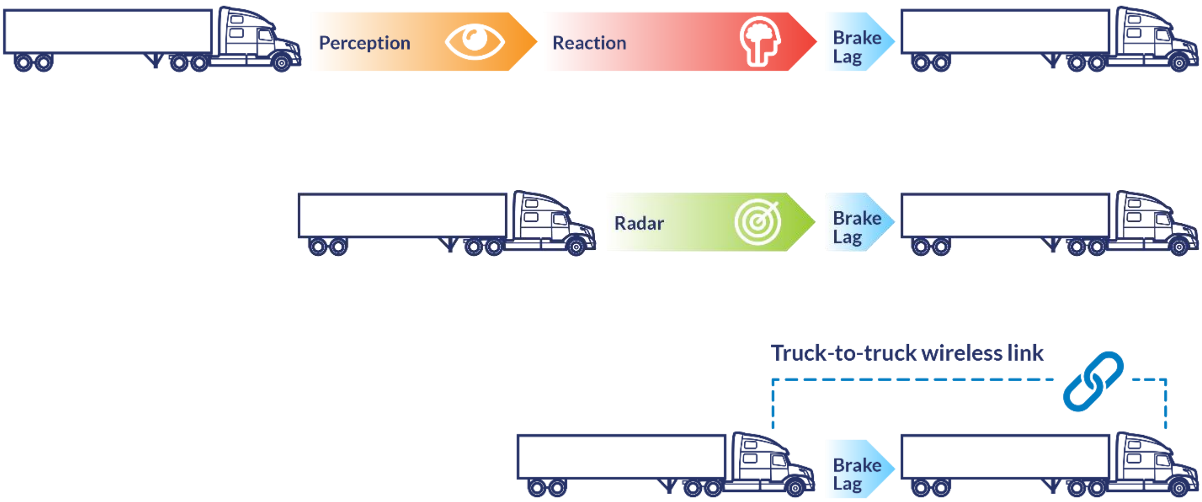

Figure 2. Differences in breaking for different technologies (Peloton-tech.no, 2017)

1.1.3 Expected Benefits

Expected benefits of AVs within the transport system and society range from increased safety and less required road space to better fuel consumption and less emissions and pollution. Although there are numerous positive expected benefits, given the current level of development and implementation, these are only predictions. Important to note that all impacts due to AVs will also affect TPs but impacts due to TPs will not affect AVs.

1,3 million were killed due to traffic accidents in 2015 (Who.int, 2017), in which over 90 % are driver related errors (National Highway Traffic Safety Administration, 2008). In removing the human component, AVs are expected to reduce the number of traffic accidents. A report by NHTSA on Tesla's driver aid feature show a reduction of 40 % in crashes per driven distance comparing numbers before and after installing Autosteer (Habib et al., 2017). Litman (2013)'s report suggest that crashes can be reduced by 90 %, including the new issues AVs will bring with them, such as cyberterrorism, system failures, offsetting behavior and rebound effects. By removing the human component, risk is altered as an AV will not take the same risks as humans have shown they are willing to take throughout the years. This include the removal of drug/alcohol-impaired and distracted humans, which is a major risk element and a danger for everyone on or around the road (Lin et al., 2016).

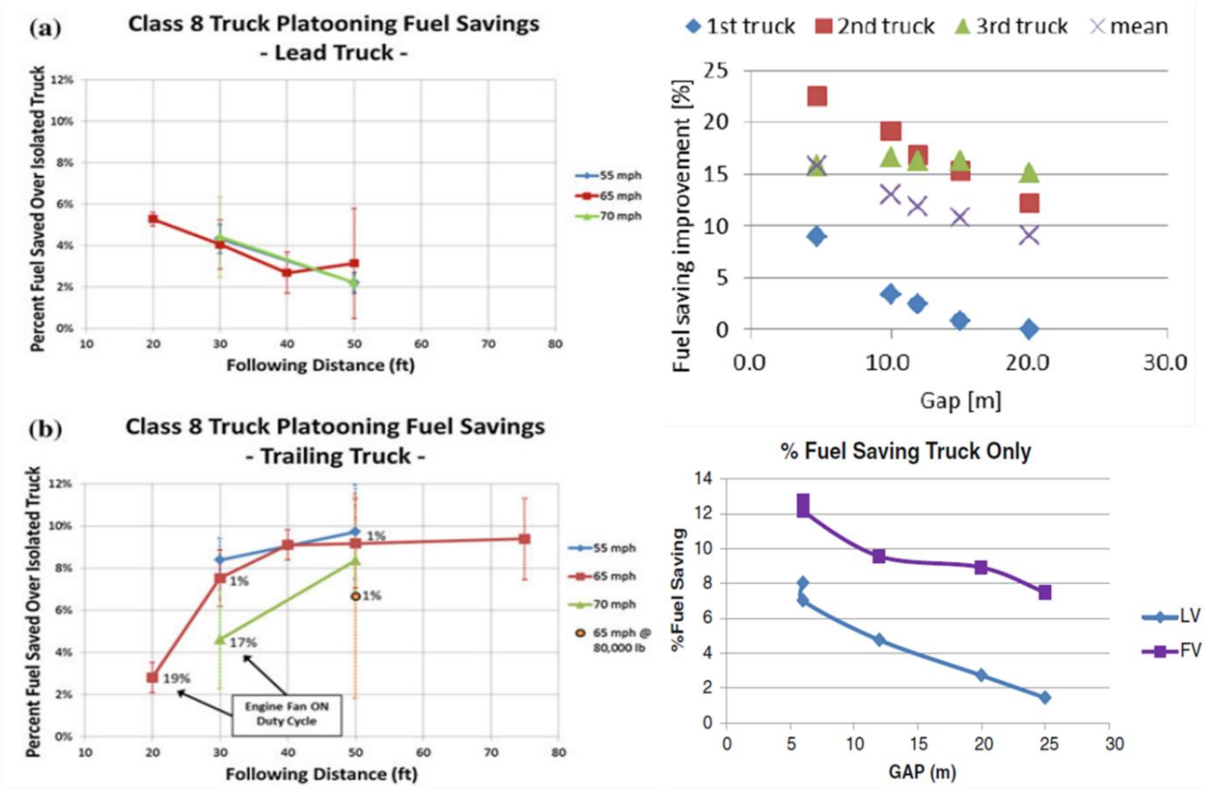

Figure 3. Real-life fuel savings for truck platoons (Poorsartep and Stephens, 2015, Tsugawa et al., 2016)

For TPs, fuel consumption and emissions have been researched and tested by several parties. All findings point at a reduction of fuel or energy demand. The magnitude of a reduction is highly dependent on the aerodynamic capabilities of each truck and trailer, as soft-sided trailers seem to get a bigger benefit from the reduced drag than rigid trailers. AV's capabilities to be programmed to drive eco-friendly, also secured better fuel economy (Poorsartep and Stephens, 2015). American based National Renewable Energy Laboratory (NREL), European based Safe Road Trains for the Environment (SARTRE), and Japanese based Japan Automobile Research Institute (JARI) all researched the fuel consumption of TPs, with findings ranging between 2-8 % for the lead truck and between 8-20+ % for following trucks (Poorsartep and Stephens, 2015, Tsugawa et al., 2016, Lammert et al., 2016). The following distance, or gap, is a big factor for the efficiency of the platoons, see figure 3, with smaller following distances resulting in better fuel efficiency. When saving fuel in a combustion engine, this correlates to a reduction of CO_2 and as the NREL project showed, reduction of NOx, which is one of the worst emissions released in urban and city areas (Tsugawa, 2014, Lammert et al., 2016). Truck platooning will both contribute with societal benefits (i.e. less emissions) and business benefits (i.e. fuel saving). The business benefit might be the most important, as this these benefits are critical for a company to decide to take use of ATs and TPs. As fuel is the second highest operating cost and accounting for about 21 %, this can be a huge economic improvement (Hooper and Murray, 2017). AVs are also likely to get an improved fuel consumption as well, as they can be programmed to drive eco-friendlier and more efficient as a result of connectivity and information received from other platforms. This benefit, though, will not be as great as what trucks in a TP will achieve by reducing the drag.

Platoons are also expected to decrease the space needed for vehicle operations. With those small distances between the trucks, the required road space for each truck will be less. As Daimler identified during their ETPC participation, 3 semitrailers (18,75m) with a platoon gap of 15 meters would only require 86,25 meters of road at 80 km/h. Compared to the usual minimum of 64 meter gaps, which would require 184,25 meters of road, saving 47 % (Ellwanger and Wohlfarth, 2017). The gap of 15 meters included additional safety margins to the smallest possible gap of 7,53 meters. Similar findings were revealed by Janssen et al. (2015), who found a 46 % reduction in required road space for two semitrailers at 80 km/h with a gap of 0,3 seconds.

Other expected benefits of TPs include reduced labor costs, asset utilization optimization, and reduced congestion or optimized traffic flow (Janssen et al., 2015). These benefits will not be realized from day one, but the effects are expected to be seen as the technology matures and more vehicles are used. These benefits are mainly for trucks and TPs, but some can be true for AVs as well. This include optimized traffic flow and reduced congestion.

1.1.4 Complex Implementation

Implementation of AVs into the transport system is a complex issue. Transport is a big part of everyday life, and a possible big change like this will influence many of parties.

The most important factor for a successful implementation is a fully functional and reliable AV. Necessary vehicle technology, as sensors, have not yet reached a level of development and high enough standard for public exposure and use. As described in the theory chapter, different sensors are used for different tasks as well as giving the system a redundancy in case of single sensor failures. Some of the important sensors, as LIDAR, are not at a point where they are ready for mass implementation, not only because of technological barriers, but also costs. These barriers of implementations are closely correlated with safety, and without a sufficient level of scientifically proven safety, the vehicles will not get the necessary certification. Trial implementations such as Google's self-driving car project, Waymo, is using trials to learn how it (the vehicle) shall interact with other road users (e.g. human drivers or pedestrians). The vehicle uses machine learning, and the more it drives and the more it interacts with different traffic conditions, the better the vehicle gets (Waymo.com, 2018).

Acceptance is a factor that is sometimes forgotten, but surveys have shown this to be important. In the US, American Transportation Research Institute's (ATRI) survey of truck drivers and carriers showed 44 % of carriers and 54 % of drivers were unwilling to use automated and platooning systems because of discomfort, with around the same numbers unsure about the safety impacts of such systems (Poorsartep and Stephens, 2015). This is why demonstrations are viewed as necessary, to show the benefits and how the technology works, but also how safe it is. As the technology advances further, it is likely to see more of these demonstrations as manufacturers feel it is safe and necessary. A poor result in a demonstration will further develop drivers' unwillingness. Factors, such as privacy and security, have concerned a lot of people. These electronically controlled vehicles are under an imminent threat of hacking and data gathering. These concerns must be proven wrong, for the acceptance of such vehicles to rise. And similar huge infrastructure systems have been shown to withstand security threats, with power grids air traffic controls operating seemingly safe (Fagnant and Kockelman, 2015).

1.2 Research Scope and Objective

1.2.1 Research Objective

As previously mentioned, this thesis has a main goal to find what road elements and parameters are impacted by ATs and TPs. The research is part of a bigger research project conducted by the Norwegian Public Road Administration (NPRA) to update the handbooks. This research is part of the future segment and how AVs will change and influence roads. It is necessary to first gain an understanding in the difference in vehicle characteristics and behavior from a conventional truck. The following research questions will be used to guide the research to its goal.

Table 1. The research questions

Research Question	Description
1	What is the differences in vehicle characteristics for conventional trucks vs autonomous trucks?
2	What elements of road design are impacted by autonomous trucks and/or truck platoons?
3	How can these elements be improved to be supportive of autonomous trucks and truck platoons?

Table 1 shows how the research questions point towards the overall goal. Through the literature review, it was discovered that the future physical infrastructure is not a heavy researched topic. Because of this, it was considered the best if the research questions started at the bottom with examining the differences in truck characteristics. As the road design is calculated on vehicle characteristics, a change in those characteristics imply that also the design of roads will change. Possible changes will be discussed.

1.2.2 Defining the Scope

This research shall examine what road design elements will be impacted by AVs by completing the research questions from table 1. A literature review, document review, and interviews will be used to answer the research questions, ending with a case study to help show the results.

This triangulating of sources ensures the answers will reflect the views of civil engineers, truck manufacturers, and researchers. The results will build upon road design handbooks and look at the basic parameters of road design, the thesis will therefore be written more for road designers than any of the other groups. Researchers might find the results interesting, as the goal is to conclude with further actions needed to ensure new standards for roads to be supportive of ATs and TPs.

The research is conducted as part of the master's thesis at NTNU, and took place during one semester, the spring of 2018. The research is performed by one person, and this time limitation made for a concise research scope. The author of this thesis is taking a master's degree in road planning and design, and parameters closest to this will be examined. Structural loading, which is a big part of truck platooning, will be mentioned but not proper researched. Instead, geometric alignments and road elements such as bridges, tunnels and intersections will be important topics. This is not a thesis on how ATs or TPs can be implemented, nor is it about the technology they possess. These topics will only be mentioned in a way to describe how these technologies and trucks work, as it is important to know when designing a road.

1.2.3 Assumptions

The penetration of AVs is a very decisive factor when looking to change the existing road design to be more supportive of AVs in general. With connectivity, AVs can operate with less infrastructure than today, but as long as the traffic conditions are mixed, this infrastructure cannot be changed. Because of rapid development of technology and machine learning, vehicles are improving every day. It is a fair assumption that these vehicles will surpass conventional vehicles' safety and reliability and join the public market at some point in the future. For this thesis, assumptions are made on penetration, and proposed solutions are for full penetration of AVs, both trucks and other vehicles. This either mean a full penetration of AVs in the market or roads specifically made for AVs and only AVs, aka classified autonomous roads.

Currently, OEMs are researching automation level 3, 4 and 5. According to several sources, it is extremely difficult to predict when AVs are considered "good enough", and when they will be released and fully implemented. There are many decisive factors, including technology, acceptance, authorities and so on, that accurate predictions are near impossible (Janssen et al., 2015). Policies and standards for how AVs should operate and function must be finished, setting clear restrictions for how the vehicles must be built, similar to today's conventional vehicles. This thesis assumes that by 2050, new road standards for AVs should be complete, and AVs should have reached level 5. This thesis will therefore only consider the highest automation level (level 5), as this level will have the largest effect on the road design.

Today, testing and researching are difficult because of the restrictions caused by policies, laws and conventions (see section 1.1). This is assumed to be solved by 2050, with international standards making it easy for the vehicles to cross borders. The same goes for the technological side of AVs. The problems with costs and performance of some sensors are gone, and the vehicles are assumed to be functioning properly.

1.3 Structure

The goal of this master's thesis has from the start been divided into two; produce a scientific paper and a normal thesis. The reason for writing a scientific paper mostly being the confidence of supervisor Kelly Pitera and her thoughts that the topic would have a place beside other literature and research. It would also stand as a challenge for the author, a good experience and useful learning to bring into the workplace. The abstract was accepted to the European Transport Conference (ETC) 2018 in Dublin. The content in both the scientific paper and thesis are mostly the same, though the thesis has more detailed and expanded chapters, while the scientific paper had to be more concise to keep it at as few pages as possible.

This master's thesis is divided into three parts, where part 1 consists of the thesis, part 2 is the scientific paper, and part 3 consists of the appendix. See figure 4 for complete setup.

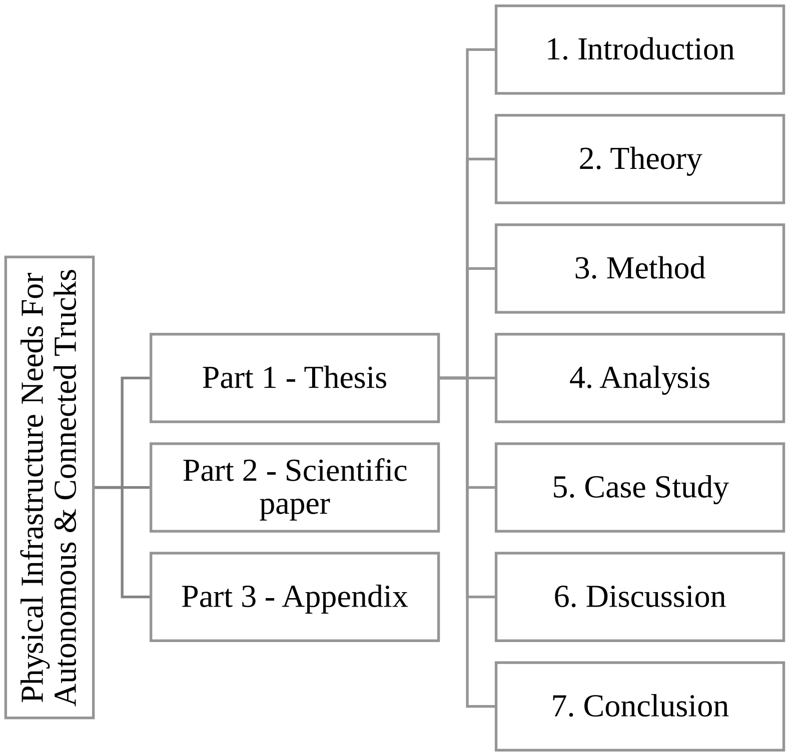

Figure 4. The master's thesis' structure

2 Theory

This chapter looks at the theory behind AVs, how the sensors work and their weaknesses. This is important to understand to find good solutions for road design. Existing infrastructure will be presented, divided into the categories of digital and physical. Although this thesis concentrates on the physical infrastructure, it is closely correlated with the digital and knowledge about this subject is also necessary. How the geometric road design is built up of basic parameters will also be shown, as this has a major impact on the conclusion.

2.1 Autonomous Vehicles

This section will go through each of the most common sensor types currently in use and look at what they contribute with. It will also present and explain connectivity technology.

An AV's ability to navigate is based on information gathered through different types of sensors. That data is sent to a processing unit. This unit, much like a human's brain, combine the different sensors into a picture of the surrounding world, a process that is often called *Sensor Fusion* (McGehee et al., 2016). The different sensors have different tasks and have their own strengths and weaknesses, as expanded on below. With today's technology, normal sensors include ultrasonic, image (camera), RADAR (Radio Detection and Ranging) and LIDAR (Light Detection and Ranging) sensors. It is important not to forget "the cloud". It might not be a sensor the same literal way as a camera, but it will contribute with information that is out-of-sight of local perception sensors. When combining these images of the surrounding world with high-precision GPS and detailed digital maps, the vehicle will be able to control itself (Volvocars.com, 2017).

2.1.1 Sensors

The following information is taken from 2025ad.com (2017) and McGehee et al. (2016)'s summaries of sensor technologies. It is important to remember that different manufacturers and researchers might use different technologies, and all sensors might not be used on all vehicles. At the same time, the development is so fast that what is currently state of the art, can have changed in 2050, according to an interview with an OEM. It can therefore be difficult to use specific sensors in the following analysis.

Ultrasonic sensors are no longer being researched as they are good enough for the tasks they need to perform. They serve the purpose of short range detection of objects and does this by sending out sound waves. These waves create echoes when they hit objects, exactly like what bats use to navigate. Because of a very short range, maximum 2 meters, this sensor only works at low speeds and its main purpose is therefore for automated parking.

Image sensors works the same way as the human eyes. They look at the surroundings and detect colors and fonts, making it possible for the vehicle to read signs, traffic lights, markings and more. They can also determine range, and because of these characteristics, they work great as a back-up system, should other sensors fail. Image sensors have currently a range of about 120 meters, which developers want to increase to 250 meters. Harsh weather conditions, such as fog, rain or low sun, decrease the success rate of successfully finding and identifying objects. This sensor must therefore be developed further, and it must also be able to more precisely recognize pedestrians and cyclists which is currently at 95 %.

Short and long-range RADARs are surrounding the vehicle and work the exactly same way as on ships and planes. They send out electromagnetic waves and will detect range and speed of objects reflecting the waves, up to 250 meters. As this creates a redundancy of sensors doing the same thing, the safety is increased. The biggest problem is that RADARs currently cannot detect an objects height (2D), causing it to not know the difference of stopped cars or an overhead bridge. Newer 3D RADARs should solve this problem.

LIDAR sensors uses laser beams to scan the environment, and combined with image sensors, they can identify objects. This creates a live 3D image around the vehicle, which is also able to measure distances. It currently works up to about 200 meters. Issues come in form of costs, as the sensors need rare metals, making them very expensive ($30 000 to $85 000). Experts hope LIDAR will go through the same process as personal computers, going from expensive and large buildings to relatively cheap, pocket sized "supercomputers" (Mitchell, 2017).

2.1.2 Connectivity

It might not be a sensor in the more traditional way, as those explained above, but it is extremely important for AVs to be able to see longer than the *local* sensors' range. Using connectivity between vehicles and infrastructure, information about the road ahead is obtained. This could increase safety, efficiency and eco-friendly driving. The shared data include speed and characteristics of the vehicle, warnings about objects, animals or difficult conditions, foresee traffic jams, accidents, and traffic signals. It makes it possible for the vehicle to operate in the most efficient way possible, and thereby reducing the energy consumption (Pype et al., 2017). It allows the vehicles to "see" beyond the 250 meters the normal sensors give, but the system also need a big enough fleet of connected vehicles to keep the data updated. The connectivity element is not a necessity for AVs to be able to operate, but it is a great aid and will likely increase the benefits of fuel saving and safety.

Highly detailed digital maps are seen as a way to improve safety, but it could also be used to remove lane markings, signage and other message boards. This is not possible until either the entire vehicle park is autonomous or a road allows autonomous driving only, as conventional vehicles will require these elements (Hayeri et al., 2015). It is important not to forget soft users in a case like this, and infrastructure supporting these users must be established if there are crossings or other interactive elements along autonomous roads.

If the data provided by AVs cannot be accurately pinpointed, the data could become a risk rather than a benefit. The system must be able to give instructions or recommendations that are precise and specific enough for that current situation the vehicle is part of (Böhm and Scheider, 2007), otherwise the instruction will be hard to understand and might cause more problems than they solve. Most have opted to use Global Navigation Satellite System (GNSS), though it has flaws. It cannot operate inside tunnels or multilevel car parks, and it will struggle in cities with high-rises (urban canyoning). Signals can also be jammed or tampered. There are several solutions being worked on to get the accuracy as high as possible and making the system extremely reliable, but none are completely finished (Knoop et al., 2017).

2.2 Infrastructure

The infrastructure needed to support AVs, ATs and TPs can be divided into two categories, digital and physical. The digital infrastructure includes Intelligent Transportation Systems (ITS) and Information and Communication Technology (ICT), and it allows sharing of relevant information between entities, allowing vehicles to know about conditions further ahead, road operators to know about the roads condition and so on. The physical infrastructure is not as heavily researched, with most of Norway's road design handbooks based on knowledge from the 1950s and 1960s. The physical infrastructure includes the geometric alignment, road surface, sub base, roadworks and AV certification (Huggins et al., 2017). For this thesis, the physical infrastructure specifically means geometric alignment and road elements (i.e. widths and other specific elements like junctions and bridges).

While this thesis does not examine digital infrastructure, it can play a major role for AVs and how the physical infrastructure should be designed. It is therefore important to have a certain understanding of this topic. At the same time, this work focuses on a specific vehicle, AT, along with considering the operational condition of TPs. The physical infrastructure need to be updated to be ready for the implementation of these trucks, and with constructions often taken a long time to complete, it is important that the road design handbooks are updated quickly.

2.2.1 Digital Infrastructure

A big part of the digital infrastructure is how it use ICT to gather, store, manage, and exchange data. An important role here is data management, as it manages of all the gathered data. This could be from the AVs sensors, roadside infrastructure, or other providers. Automakers and other companies (e.g. TomTom) want to map roads, by adding all relevant attributes to highly detailed 3D maps. This require several parts to work together as road operators have the roadside ITS infrastructure, automakers have the sensors and data from their AVs, and other companies can have other roles (e.g. location services). The data management must take all this data, combine what is relative, and share it with all parts. To be able to do this, ICT is a necessity. It can be cellular, WIFI, radio, satellite, or DSRC (Dedicated Short-Range

Communication). As well as communicating with the infrastructure, this technology is necessary to allow for inter-vehicle communication.

The digital infrastructure is an absolute necessity to allow for TPs. Major milestones that need to be solved for the digital infrastructure to be considered good, are affordable sensors, high-precision positioning, communication technology, and highly detailed maps (Sanchez et al., 2016).

2.2.2 Physical Infrastructure

Because a vehicle will interact with the physical infrastructure, this is a key element in how well a vehicle performs. Huggins et al. (2017) mentions there are different types of AVs coming, with different characteristics, the road must be capable of handling them all. The readability of the road environment is one of the most important factors, as this makes them able to see where they should drive, as explained in section 2.1 about a AV's sensors. This includes road signs, lane markings, and pavement conditions. With AVs inhabiting different vehicle characteristics versus today's conventional vehicles, the geometric design, together with widths and certain road elements, are set for possible changes. Depending on stopping sight distances and speed, this could make roads cheaper to build as it allows them to better follow the natural terrain.

One of the main points from the Huggins et al. (2017) Austroads' report, is the importance of an international standard for roads and surrounding equipment used by AVs. This would make it easier for the vehicles to travel over borders, as, for example, the signs would be similar. The report also asked manufacturers for their opinion on issues with the physical infrastructure. They mentioned signage, line marking and pavement conditions as big problems for self-driving cars. Signs are not consistent with fonts, spacing, wording and conditions, which in term has a negative effect for the success rate of readability for the vehicle's sensors. Electronic signs, based on LED, have issues with refresh rates, making the signs hard to read for the vehicle's cameras. They have also gotten reports that sign locations are not consistent, sometimes causing cameras to not be able to pick up the signs. For lane marking, the problem seems to consist of variability and visibility. Again, causing problems for the vehicle's sensors to pick them up. Uneven and cracked pavement can cause the sensors to believe there are lane markings or other objects on the roadway.

Today's roads were never designed to cope with TPs. Elements such as roundabouts, bridges, intersections, and on/off ramps were designed for single vehicles with a different set of characteristics, including lengths and loads. As a TP can be viewed as a single unit, the load dynamics will be different, causing higher stress on structural elements. Overtaking opportunities might not be long enough, the same goes for on/off ramps. SOS-areas and other areas beside the roads will possibly have issues with the lengths as well. Huggins et al. (2017)

also mention the problem with tolling, as it can be hard to distinguish the vehicles from each other with existing tolling technology.

Geometric alignment and design are dependent on two main parameters, vehicle performance and sight distance (Washburn and Washburn, 2018), further expanded on in section 2.3. At a point, the performance of vehicles will no longer be the dimensioning factor but rather the comfort aspect. Washburn and Washburn explain that because of safer vehicles, passive safety measures can be reduced, which will reduce the weight of vehicles. This could lead to higher speeds for the same amount of energy. This will impact alignments, as humans have tolerances of what is felt comfortable and not. It is important to remember that a roadway usually is used by several different types of vehicles, and that trucks will use the same roads. Especially during climbs, trucks lose a lot of their speed. A 15 mph decrease in speed related to the average speed makes the truck 9 times as likely to be involved in an accident (Glennon, 1970). The difference in speed is important and must be considered when designing the road and deciding the speed level, as it can lead to lower crash rates.

Because of an AV's precision, lane widths could possibly be reduced, together the removal of median barriers. A four-lane road could end up having enough cross-sectional space to convert it into a five-lane road. It is important to remember that emergency vehicles should be able to pass and therefore, it must be enough room in case of such an event. It should also be enough room for a broken-down vehicle to stop on the roadside without being inconvenient for other traffickers. These clear-zones, or shoulders, must remain a sufficient width (Hayeri et al., 2015).

Structural design will not be a topic for this thesis, as the research on this topic is lacking, but it is worth mentioning possible issues. Close proximity driving, especially with heavy trucks, and the same point of contact for all vehicle will change load volumes and dynamics. New and faster wear patterns will emerge, but it is depending on type of use and traffic conditions (Lutin et al., 2013, Chen et al., 2016).

The Huggins et al. (2017) report also mention problems with roadworks and AV certification of roads. Roadworks will need to be researched further, as this can cause problems as the environment is different than what is shown on the digital maps. This will not be looked at in this thesis. AV certification is how some roads are certified or supportive of AVs. During a transition period, it is likely to see more of this certification used, to divide the different types of vehicles. This would increase the safety and show the benefits of buying an AV.

2.3 Norwegian Road Design

Road design in Norway is based on vehicle characteristics from the 1950s and 1960s, only updating the numbers to better fit today's more modern vehicles. The requirements and design rules are presented in several topic-specific handbooks published by the NPRA. As the handbooks are based on older knowledge and calculations, the NPRA has decided to examine if possible improvements and bigger updates are necessary. This thesis is a part of that research, specifically the future road design with AVs.

The most important handbooks for road design are N100 and V120. The N100 handbook states the requirements and guidelines for building new and upgrading existing roads and streets, as well as some overlying information regarding different road elements. Handbook V120 show how the requirements and guidelines of N100 are calculated. This handbook goes deeper into the how, why and what is responsible for the results in N100.

2.3.1 The Basic Parameters

The geometric design consists of many formulas and parameters that together build all the requirements and guidelines for the alignment of a road. All requirements are based on the basic parameters, and all calculations are started with them. These parameters are very important in that they are responsible for how a road function. They consist of constants parameters, varying road parameters, and varying vehicle parameters. Their divided into 4 categories, dependent on where they are found and what they relate to; statistics, impacts on vehicle/driver, surroundings, and driver. All the basic parameters are shown in table 2, with their corresponding values.

Table 2. Basic parameters for geometric design

The Basic Parameters			
Statistic Variables		**Type**	**Value**
Eye height	a_1	Constant	1,1 meters
Object height	a_2	Road parameter	0-0,65 meters
Vehicle height	a_3	Constant	1,35 meters
Vehicle width	b_k	Vehicle parameter	Design vehicle
Wheelbase	b	Constant	1,65 meters
Overhang	b_o	Vehicle parameter	Design vehicle and curve radius
Track increase?	b_s	Vehicle parameter	Design vehicle and curve radius
Variables Related to Impacting the Vehicle/driver			
Design speed	V	Road parameter	30-110 km/h + add-ons
Acceleration	a	Vehicle parameter	Varying
Retardation	r	Vehicle parameter	3,0 m/s^2
Vertical acceleration	a_v	Road parameter	0,3-1,0 m/s^2
Relative vertical speed	v_{vf}	Road parameter	0,05-0,06 m/s
Variables Related to Surroundings			
Total friction	f_t	Road parameter	Varying with speed
Breaking friction	f_b	Road parameter	Varying with speed
Side friction	f_k	Road parameter	Varying with speed
Superelevation	e	Road parameter	3-8 %
Gradient	s	Road parameter	Max 5-8 %
Variables Related to the Driver			
Reaction time	t_r	Constant	2 seconds

2.3.2 The Road Alignment

The N100 show the requirements for the alignments on the different types of roads and streets used in Norway. The geometric minimum and maximum values are calculated from the basic parameters, and their correlations are shown in figure 5.

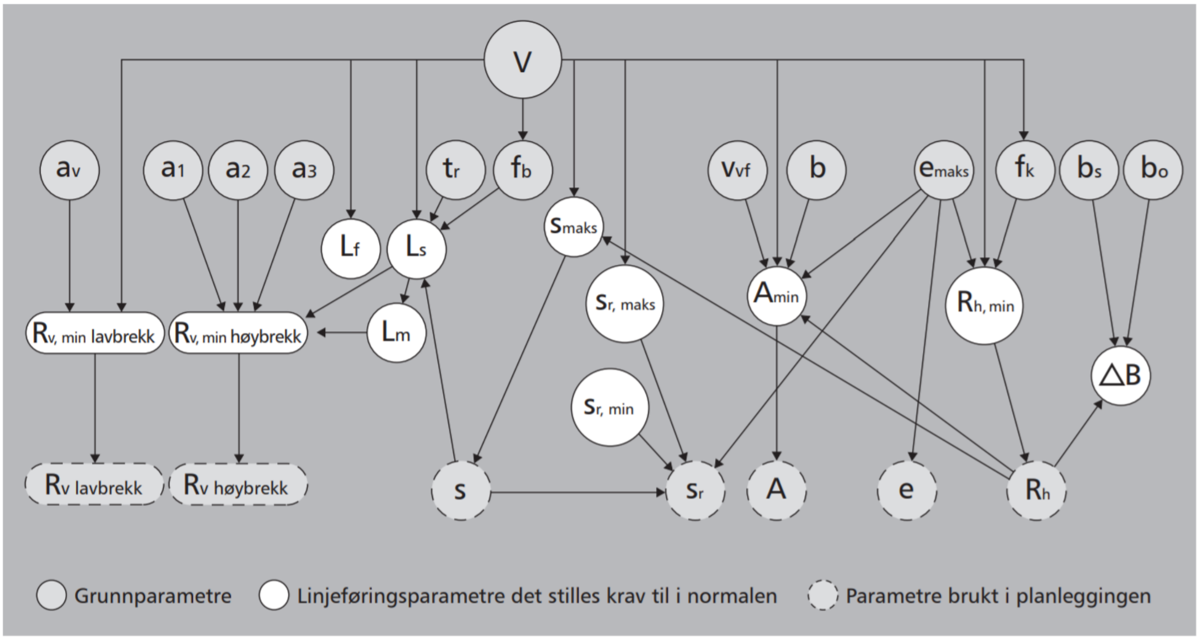

Figure 5. Correlation between the road parameters (NPRA, 2014)

Speed

Speed is the main parameter and can be described with or without safety add-ons. As shown in figure 5, the speed (V) affects all of the design parameters directly or indirectly, except superelevation. This is the crucial parameter and it decides how a road is built. This is why the speed must be decided before starting the planning and design process of a new road.

The speed add-ons can be divided into two categories; safety margins and safety add-ons. Both try to increase the safety by minimizing the risk. Safety margins are added on to the speed limit to increase the design speed and thereby the minimum requirements. It is done by a risk analysis, where higher speed and more vehicles create higher risks and consequences. This helps design roads that are a bit better than what their speed limit actually says, thereby increasing the gap from speed limit to an area of too much speed, where friction is lost or an accident is much more prone to happen. The speed add-on is due to humans driving faster when curves are bigger. This should help increase the safety, aka reducing the risk for accidents. Together, these add-ons can increase the design speed of 10 km/h above the speed limit.

Curvature

Vertical and horizontal radiuses are very important for how the road feels to drive. As explained above with speed add-ons, bigger radiuses make some drivers go faster. It is therefore crucial that these radiuses are well designed, as they keep the average speed level around the speed limit. As seen in figure 5, the three design parameters $R_{v\ lavbrekk\ (sag)}$, $R_{v\ høybrekk\ (crest)}$, and R_h are all decided from their minimum requirements. This is because the speed influences how sharp the radiuses could be, meaning that at a certain speed the minimum radius is what is deemed safe and/or comfortable. The sag radius is affected by the vertical acceleration, this is a parameter used for comfort and ensures that the human bodies does not feel too much forces when driving through a sag curve. The crest radius has the most parameters influencing it. As the vehicle is going over a crest, sight is an important factor and it is therefore influenced by all heights (eye, object and vehicle height), as well as stopping sight distance. The horizontal curves are maybe the most important parameter to keep drivers from speeding, as it has a big role in representing the feel of the road. The minimum radius is influenced by the side friction, maximum superelevation, and speed. If the speed is too high compared to the superelevation and side friction, the vehicle will not make it around the corner.

Sight

Sight is important for several design elements and can be divided into 4; free sight distance, stopping sight distance, meeting sight distance, and overtaking sight distance. The free sight distance is not represented in figure 5, as this parameter just says how far a driver should be able to see in a continuous and visible roadway/line. For a 4-lane road, the only demand is that stopping sight distance is met. This is decided by adding the reaction distance and the breaking distances together. Parameters needed for this is speed, reaction time, breaking friction, and gradient. For 2-lane roads, this distance will be calculated in the exact same way, but here it is also a requirement that there are enough overtaking stretches, so the overtaking sight distance must be satisfied. This is calculated using a calculation model in Excel. For roads narrower than 2-lanes, meeting sight distance is crucial, as two vehicles are operating on the same lane, but in opposite directions. This is set to two-times stopping sight distance with a safety margin of 10 meters added on. These sight distances must be controlled from vertical and horizontal alignments, and necessary steps must be taken if they do not meet the minimum requirements.

3 Method

This chapter gives an insight into the different methods used to gather data for this research. The master's thesis is an exploratory study of future road design requirements for ATs and TPs, using gathered information and data to analyze the topic. The methods used are literature review, document analysis, interviews and a small case study.

Research is described as a process to get knowledge and data (Dalland, 2000), and the choice of method can heavily influence the results. Factors as time, availability and feasibility should be involved in the decision of methods (Dalland, 2012), though the chosen methods should mainly be based on the overall research goal and the competence of the researcher.

Based on the overall goal, time, and a pre-study of existing literature, qualitative research methods were chosen. These methods often deal with limited data which is studied thoroughly, this build up the researchers understanding and experience which is then used for the analysis. The existing literature showed a very young research area with minimal field implementations. Within this study focus, there is limited existing quantitative data, compared to existing qualitative information (based on words, sentences and reports) (Dalland, 2000, Dalland, 2012). Literature review, document analysis and interviews were chosen mainly due to the limitations of very little research on the topic. Thus, these qualitative methods are not only good choices for a topic with scarce literature, but also beneficial to use when there are requirements for openness and flexibility within the research question (Thagaard, 2013).

The first part of the analysis examined the differences between future ATs and today's conventional human-driven trucks. The analysis focused on the performance characteristics linked to the basic parameters of road design, influencing the geometrical design. This related to both truck parameters (e.g. power, weight, length) and driver parameters (e.g. reaction time, awareness). Most of the driver related parameters were found through a literature review, as there have been some studies on how autonomous driving affects the behavior of the vehicle as it changes driver from a human to a computer. Interviews with truck manufacturers of autonomous technology were conducted to get the missing information and data that the literature could not provide.

The second part analyzed how the differences between current and future trucks would impact existing physical road infrastructure. To be able to conduct this analysis, it is necessary to have an understanding for how road design works. A document analysis of Norwegian road design handbooks gave the expertise of the underlying calculations of road design parameters. The analysis was complemented by the existing research published on future physical road infrastructure. The document analysis is often used in combination with other methods, something that ensures triangulation. This increase the reliability of the research results and offer a more well-thought-out conclusion as data is gathered from separate sources with a greater possibility of a difference of opinion (Bowen, 2009).

The third phase of the analysis involved discussions regarding possible changes to road design. The three methods of literature review, document analysis and interviews gave a deep understanding of the topic and allowed for discussion on the implications of various changes for future roads.

A summary of all the methods used in each phase is found in table 3.

Table 3. Applied methods for each research question

	Research question 1	**Research question 2**	**Research question 3**
What	What is the differences in vehicle characteristics for conventional trucks vs autonomous trucks?	What elements of road design are impacted by autonomous trucks and/or truck platoons?	How can these elements be improved to be supportive of autonomous trucks and truck platoons?
Method	Interviews and literature review	Document analysis and discussion	Analysis and discussion

The last part of the analysis consisted of a small case study, comparing the possible changes to make a road autonomous and truck platooning supportive with an existing Norwegian road. This method was used to apply the results of early stages of the research on an existing infrastructure scenario, with a goal to facilitate the best possible solution to achieve the most of AVs' benefits.

This research has an exploration approach to the topic. Due to the scarce research on future physical infrastructure, this is characterized as an *exploratory study*, which Blumberg et al. (2011) suggest as a smart choice when there is not a specific idea, definition or clarity surrounding the problem. Exploratory research is a good way to create a basis for further and more specialized research.

The overall goal of this thesis is very wide, and due to limitations of time, scope and manpower, it is impossible to thoroughly research all parts of the topic. This thesis will therefore conclude with some specific points of possible impacts that are likely to happen and where more research is needed.

3.1 Literature review

Blumberg et al. (2011) explains a literature review as method to provide the researcher with information about previous theories, ideas and research regarding the relevant topic. It provides a review of related research and have a goal of providing an empty spot in which this research can contribute. It shall also be the basis for any discussion of the research's results (Blumberg et al., 2011).

Even if the quantitative research on the field is scarce, the knowledge a few provides are viewed as important data for this research. The qualitative data and knowledge presented in the literature, open the possibilities to explore the topic through discussions and analysis. As this method is very important and is used most throughout this thesis, literature review is considered the main method.

The workflow was divided into two sections, one during the pre-study and one during the research and thesis period. The pre-study gave a good basis to formulate the research goal, research questions, and enough understanding of the field to decide about other possible methods that could be used. Due to the time limitations of a master's thesis, it was important to evaluate the scope and the extent of the research as early on as possible. During the research and analysis period, the literature provided, in addition to the underlying knowledge, information used in the introduction and theory chapters. By showing to previous research this early, a space for this thesis was easily obtained through the definitions and scope of the research questions. It also gave a clear understanding and explaining the technological aspects related to the vehicles and infrastructure.

The established literature came in form of journal articles, standards, reports, websites and books. Most of the literature was gathered on Google Scholar or Google Search, which provides a good way to check authors and how many times their research has been cited. In some cases, NTNU's online library, ORIA, was used. This was used to find relevant books, due to its large online inventory, or when Google Scholar could not find certain sources cited in previous literature. The search strategy started with a wide specter during the pre-study and got narrower as the knowledge increased. Keywords used included truck platooning, road design, physical infrastructure, autonomous vehicles etc.

At the start, all searches were done in English, making an assumption that much of the relevant research had either been published in international journal or conference proceedings. As the knowledge increased and the scope got narrower, some searches for specific subjects was done in Norwegian. As this thesis examined the topic of Norwegian roads, specific research conducted by Norwegian institutes would have been a good addition. However, there is little to none research on this field except for some ITS and physical infrastructure projects started by the road authorities, NPRA. These projects had just started[1], and had yet to produce publications.

[1] NPRA's projects started in 2017 and early 2018, with nothing published when this thesis was written.

3.2 Document Analysis

An analysis of scientific documents is not the same as a literature review. Where the literature review is an activity to find background research and ultimately find an empty spot for your own research, the document analysis consists of interpretation a document's data and use that for your own research (Reseachomatic, 2012). In this thesis, Norwegian road design handbooks and technical drawings were analyzed.

Handbooks from NPRA surrounding road design and road construction provided data for how existing roads are designed, and how and what decides the different requirements. Most used were N100 and V120, as they are related to the road design and alignment. N100 (*Road and Street Design*) gives the design requirements for different road types or provides information on other handbooks to use for more specific information on different elements. V120 (*Premises for Geometrical Design of Roads*) provides the background theoretical information used as the basis for N100, including how requirements are calculated, definitions and so on. Together, they are the most important manuals for road design in Norway. Other manuals used with varying degree are N101 (*Railings and the Road's Side Areas*), V160 (*Road Railings and other Traffic Safety Measures*), N400 (*Bridge Engineering*), and N500 (*Road Tunnels*).

The analysis of the Norwegian road design handbooks was conducted after the literature review had provided enough knowledge of platoons and AVs to understand how they function and what their likely strengths and weaknesses are. With this knowledge, each basic parameter of road design could be evaluated to determine if it is impacted by AVs or not. This is one of the essential parts of the research, as the road design requirements are calculated using these basic parameters, which is. The design parameters (e.g. alignment, gradient) could be changed through their formulas, depending on how AVs impacts the basic parameters. These parameters, as described previously in section 2.3, is what the roads requirements are dependent on. Together with further literature reviews, this revealed missing information surrounding the basic parameters, and would need to be a part of the interviews. For example, it is likely that AVs will change the current reaction time, but the literature cannot give answers as to what a new reaction time could be. This is essential, as it influences sight distance and vertical alignment.

Other documents include technical drawings of a Norwegian road project between Vinstra and Sjoa. The analysis of these drawings helped understand how roads are designed as well as finding different road elements impacted by ATs and TPs. The drawings were acquired through ÅF Engineering, who planned and design that stretch. NPRA, as road and project owner, gave their permission to use them for analysis. The road is part of E6 between Oslo and Trondheim, and which continuous further north. It is an important road for transport of both goods and people, but it also represents a type of road which should be able to support truck platooning. As that specific type of road is very common in Norway, the drawings were used to look for more element-based issues regarding AVs and TPs. Completed in 2016, the road is a modern 2-lane highway and features what existing design handbooks require from a road.

The analysis of the technical drawings did not look at specific elements of that specific road stretch, but rather a more general view of road elements. What elements could cause problems for an AT or a TP? This, of course, took use of the knowledge about AVs and TPs and their behavior gathered from the literature and interviews. This made it possible to select different elements which could present an issue, for further analysis and discussions.

3.3 Interviews

The interview's purpose was to collect information and data regarding ATs and PTs and how their creators are viewing the infrastructure and what knowledge they have gathered from tests. It is a tool to gather information through communication between the researcher and some other person of interest, called interviewee. In an exploratory study, this interviewee is normally a key person with a lot of knowledge on a certain topic. The goal is to gather knowledge and opinions from these interviewees, and then convert that into reliable and viable data (Dalland, 2012).

The collected information can then be used as a complement to the rest of the data and help answering the research questions. For this research, the goal was to get interviewees that were of high importance in their selected company, which was viewed as reliable and valid sources. These companies would have to have a AT or PT division and have experience with these technologies and concepts. They would provide information and own experiences related to tests and future predictions. As these interviewees are experts on their field, their thoughts of the future are the most important for this study, what the company stands for is not as important.

For an exploratory study, there are several viable ways of conducting interviews for this approach. Blumberg et al. (2011) explains that qualitative interviews can be divided into two categories, unstructured or semi-structured. Unstructured interviews allow the interviewee to speak freely on the topic that the researcher want information about, while with semi-structured interviews the interviewee will be asked questions where upon he can speak more freely around the more specific topic or question. While unstructured interviews could do a great job for this type of study, as it will give a wide and deep understanding of the topic, semi-structured interviews were chosen. These interviews offer the ability to lead the interviewees in the right direction, only getting the necessary information and saving time for both parts. While it controls the interview, it will also allow for discussions, increasing its value as a data and knowledge gathering tool.

Semi-structured interviews require an interview or question guide. This will allow the interviewer to keep on track and help pace the interview. It is important to be ready to ask follow-up questions to extract the exact information the research require. For this research, the interview guide was built upon the information and knowledge gathered from other methods. This made it possible to ask the correct questions to fill any information gaps, while also increasing the understanding of the topic for the researcher. This open the possibility of having a good discussion around some of the topics, possibly making the interviewee become more open.

This thesis operates with anonymity for the interviewees, this is due to two separate factors. First, the discussions can evolve around company and business secrets. To avoid the interviewees becoming closed and difficult to interview, this will avoid any information given to be linked to the companies. They will also be able to look at the transcript and deny its release or suggest changes before publishing. This should ensure a comfortable setting for the companies and its employees. For the second, the companies or its employees are not the ones who should be in focus. This is an exploratory study and the interviewees are just there to give knowledge to the researcher as experts on the field of study. Being anonymous help move the reader's focus towards the knowledge and information, which is the important part of the interview.

Process

While the goal and purpose for the interviews were clear, it involved conducting most of the literature review and document analysis before creating the interview guide. This delayed the interview process by more than planned, and as the interview were supposed to get information needed to answer the first research question, this became a problem. While working with the two other methods, gaps of missing information and data revealed itself. These gaps helped create questions, but it also meant the interview process was delayed further. The first research question evolve around the difference in truck characteristics and the research questions after it depends to a degree on those answers.

Ph.D. Ane Storsæter, working at the NPRA, had the necessary contacts in the automobile market to set up meetings and send out information for this thesis. This took longer than expected, and by the time contact had been established, it was too late to travel to the companies and conduct face-to-face interviews. According to Yin (2014), this is an important factor when conducting interviews of this purpose, as it allows the interviewer to analyze the reactions of the interviewee, as well as it is easier to keep a more normal conversation and at the same time be challenging without creating a bombardment of questions.

Both supervisor Pitera and Ph.D. Storsæter had their say on the questions and contributed with different inputs. This ensured a well-balanced and progressive interview guide, but it also demanded some more time to finish it.

Due to these issues, the time to conduct the interviews were getting critical and it was decided to send out a Google Form with the questions to allow the interviewees to choose how they wanted to conduct the interview. These people are often on tight schedules, and this was viewed as the best option to get more answers. The interviewees were told that they could answer on the sheet directly or do it over any communication platform.

One responder took contact and wanted a Skype meeting. This, however, turned out to be regarding the background of the research and how certain their answers had to be. The interviewee explained that some of the questions could be difficult to give clear answers to, either because of it was not possible to know the answer or that the answer could contain company secrets. This meeting ended without any real interview, but the company later responded on the Google Form with mostly vague and diffuse answers. Although this did not provide any real numbers or exact information, it did reveal some information that were later used for creating assumptions. The questions and answers can be found in appendix 2.

In the end, this was the only company to respond, and by that time it was too late to do anything about it. Their answers were transcribed and accepted.

<u>Reflections</u>

The interview more or less ended up as a survey, as the time had become too short for the companies to plan for meetings, mainly due to bad planning of the given timeframe for this research. By the time the survey went out, the analysis was mostly done, only waiting for small changes regarding answers and statements from the interviewees. This was not a good way of gathering data. Much of the data and knowledge that could be gathered through discussions were never accomplished, and the survey only gave diffuse and shallow answers that looked more like a sales pitch than information for research. This could be a result of not being able to ask deeper questions when interviewees are reluctant to give proper answers. The answers did however uncover the OEM’s views on the technology and its implementation, making it easier to assume different and necessary numbers for the analysis.

As the information gathered through interviews were supposed to be used in the first research question, this method should have been conducted much earlier. Better planning would have ensured a better possibility to travel to the companies and conducting proper face-to-face interviews. This would have made it easier and created better opportunities for discussions and the interviewees would likely have spoken more freely regarding the topic.

Although the interviews should have been conducted earlier, there are some advantages of conducting them at a later stage. It gives the researcher time to get the knowledge from the existing literature and thereby create a good question guide with well-thought-out questions. This makes it easier to get the information that is needed. With a bigger timeframe, this would have been a viable solution, but as it turned out, it did not work with the given time limitations.

The field of AVs is still very young, and many factors are still unknown. This makes it very hard to predict the future, with constant new technological advances bring new concepts and so on. When the questions are asking about the future and how the technology could develop, the companies have difficulties to answer as they might not know or that the answers involve company secrets or other sensitive information. This business is highly driven by being secretive and introducing new and better technologies first. These factors combined makes interviews difficult as the interviewees are likely to both struggle and be unable to talk about the information they possess.

In the end, bad planning, the late start, and long process created a very narrow timeframe where the interviews had to be conducted. This short time meant the interviews were swapped out for a survey to allow the interviewees to answer whenever they had the time. This lead to only one participant, with varying results. The impact of the interviews during the analysis has therefore been toned down, which will also impact the end result.

3.4 Case study

A case study reviews objects based on different sources of gathered data and should result in an understanding or give insights to that study (Olsson, 2011). During the process of deciding methods for this thesis, it was decided that a case study of a specific Norwegian road could, with the results from the previous analysis, be a good way to present the results of this study in a more real-life scenario. It would also provide additional analysis of the results compared to existing roads, that could be discussed further.

By using the results from the previous analysis, with data gathered from the methods above, the chosen road would be considered for conversion into a TP and AT supportive road. Comparing the existing design of a road with the results of the earlier analysis would give a possibility to show which aspects of the existing road are suitable for platooning and ATs, and highlight the areas where work is needed to convert the road to meet the new requirements.

To find a road that is common but also feature some more difficult Norwegian terrain, some requirements were introduced:

- 2-lane road
- An older road
- Tough Norwegian terrain and harsh weather conditions
- Big or important transport artery

The chosen road is E8 in Troms, between Skibotn and Kilpisjärvi. It checks off all the requirements above and the NPRA is also currently conducting ITS projects on the same stretch. The road section will be described further in chapter 5.

A case study can lack the strictness and procedures found in other methods, it can therefore be more exposed to the views of the researcher or more easily get off track. By introducing the requirements above, the results should have an increase relevance, as well as making it as objective as possible (Yin, 2014).

Database description and processing:

To undertake this case study, data about the specific road had to be gathered. The geometrical data was gathered from the National Road Database (NRDB) through the website vegkart.no, both developed by the NPRA. This database contains the relevant data needed to conduct this case study:

- Horizontal curvature
- Vertical curvature
- Road width

This databank is a way to keep all necessary road parameters gathered together in one spot with easy access. Older roads, including E8, was not registered to the databank with its original technical drawings but through a survey and regression of that data, sources close to the NPRA stated. This is done to try and describe the geometry, but it will only be an approximation of the road and it will not be exact. This is the best solution that exist today and the only data that can be used for this case study.

The data extraction can be done by API or CVS files, and although API would do a better and more advanced job, the CVS can be converted into an Excel file. This is a much faster and easier method, although the result will not become as good as with the API method. This case study is just a little part of the thesis, and the Excel method is chosen.

By converting the data to the normal Excel file format, further analysis and cleaning of the data was easy and fast. By using *if*-sentences, data based on certain assumptions were extracted and its length summarized. The assumptions used derives from the results in the prior analysis and reflects the road requirements. The *if*-sentences check if a small stretch of road is within the requirements or not, and if not, that stretch is added to the total length. This will at the end, give a total length of all three parameters, which show how much it would take to make the road supportive of TPs and ATs.

The three different parameters of width, horizontal curvature and vertical curvature all had their own Excel files, as each segment of road are of different lengths. The correlation that should occur between horizontal and vertical curvature cannot be seen in these findings as a result of this. The analysis part consists of creating if-sentences and summarizing each length which do not fulfill each requirement.

To counteract for any errors or unreliable data, the calculations were completed with three different settings; requirements with both an increase and decrease of 10 %, as well as exactly on the analysis findings. This show how an error can influence the results.

3.5 Reliability and Validity

A normal approach of qualitative methods is through something like observations, interviews or document analysis, where the goal is to get a deep understanding of the subject. This comprehensive knowledge will then be used through the whole research. An obvious challenge related to these methods are verifiability of information that is gathered and the analyzed results (Thagaard, 2013, Samset, 2008). To avoid credibility issues, it is important to be critical of sources and information and assess its validity and reliability. It is important to ask how valid the results and data are for this study, and how reliable they are (Dalland, 2012).

Reliability in a research context is a question about how well the research have been conducted, if it is done to such a degree that the results are reliable. Is the research verifiable? How accurate are the measurements? And how reliable is the information? Reliability is an indicator of the study's margin of error, and a very reliable study will not have any random sources of errors (Blumberg et al., 2011). A reliability issue regarding qualitative research is how objective the researcher can be (Tjora, 2012). As a researcher's subjective thoughts are near impossible to avoid, it is essential that the researcher explain his role during the research. Any relations or affiliations with interviewees must be clearly stated. Personal opinions and goals should not affect the research, as this will decrease its reliability.

Validity in a research context is how well the results actually answers the defined research questions (Tjora, 2012). To ensure the research's validity, it is established an extra focus on a clear coherence between research questions, theory, information gathering and analysis. And it is through this chapter made clear how the research, gathering and analysis have been conducted.

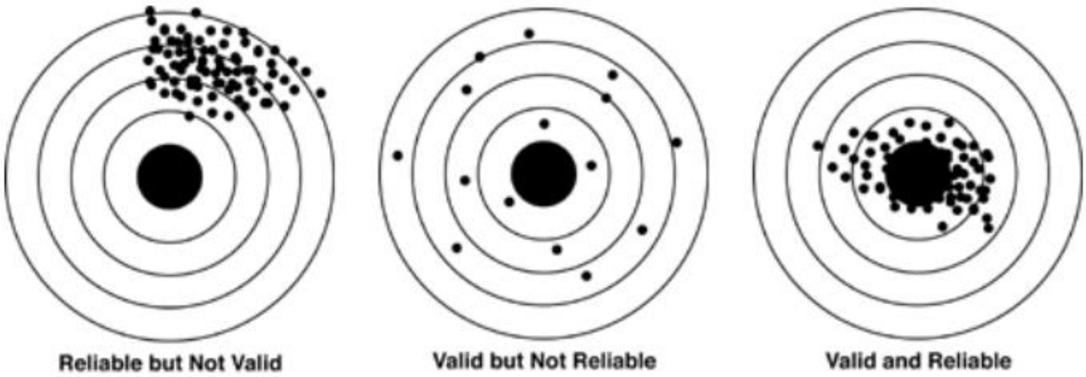

Figure 6. Relation between valid and reliable data (Columbia.edu)

As validity is measure of how well the results align with the theory and reliability is measure of how consistent the information is, figure 6 shows their correlation. A research project wants to end up with reliable and valid data and results.

The research conducted in this thesis are based on information from several methods, which should give it a high reliability. Relevant information and data are gathered through document analysis, literature review and interviews. Though interviews can be a source of non-reliable information, the triangulation of three different methods should ensure high reliability and validity for these qualitative methods (Corbin and Strauss, 2008).

Each source of data or information were checked according to NTNU's own guidelines for reliable and validated sources, called VIKO (Ntnu.no, 2018). Each step of that process is shown in table 4. By following this guideline, sources of error should be minimal.

Table 4. NTNU's guidelines for reliable and valid sources (Ntnu.no, 2018)

Criteria	Description
Reliability	The author's education and background contact info, what publisher is used?
Objectivity	How is the data presented, are the data consistent with earlier research, are the authors trying to convince or inform?
Accuracy	Is the data new, is the research process explained, does different sources end up with the same results?
Aptitude	How well does the results comply with your needs, are the results relevant for your paper?

Literature Review

During the literature review, sources could easily be checked on Google Scholar, due to their citing mechanism and profile page. To obtain valid data, all published information would first have to be relevant. This was done by first looking at the title, then the abstract, and then reading the report or paper. If something did not correspond to or was related to this study, it would not be taken to the following step.

However, due to a very young field with little existing literature, there were certain sources that did not oblige to all 4 requirements. As information was scarce, the reliability requirement was turned down when the other requirements were met, and they provided valid information. This could affect the results, but it seemed necessary as it provided certain crucial information and data. These less reliable sources were often tech, news or well-established websites. Due to the rapid development of AVs, reports and papers are not keeping up with the pace. These websites were some of the first to report the newest results and it seemed necessary to establish the relevance of this thesis for a longer period. This literature was minimized, but when used, several different sources were often found to ensure as reliable information as possible.

Document Analysis

As with the literature review, the reliability and validity are important to ensure a trustworthy result. NTNU's VIKO guidelines and criteria was used for these sources as well. The Norwegian design handbooks are both reliable and validated, as they have been used for road construction for decades. The technical drawings are reliable, because they are based on the design handbooks and standards and must be within the limits set by both Norwegian and

European authorities. However, the drawings used were not the finalized version, small changes were made during the timeframe of construction. These changes mainly consist of small changes to railings and fences and not likely the big road elements this thesis focuses on. This should not present any problems for the integrity of any results.

Interview

The sources are reliable, as they were people of high status with a great knowledge regarding ATs and TPs. But the results are not the best and the validity is a bit off. Due to the issues with the process and the change of style, the results did not turn out as hoped.

Case Study

The data used for the case study was both the results from the prior analysis and from the NRDB. Both places can be unreliable, as the methods for the analysis did struggle to find a lot of data and the NRDB did not have the specific technical drawing data but rather a best approximation of the road. It is therefore likely that the results of this case study are somewhat wrong. To counteract for this, calculations was done with both an increase and decrease of 10 % of the requirements. This show how concentrated the findings are and what an error in the requirements would do with the results.

4 Analysis and Results

This chapter aims to investigate road design elements that is impacted by either ATs or TPs, using the methods previously described. Examining both existing and new roads, the results will consider new standards for impacted parameters within road design.

To cover the widest possible range of roads in terms of traffic volumes, speeds, number of lanes and so on, three different road types have been used during this analysis. The current 2018 handbook N100[2] present 5-6 different roads, categorized as *Main roads* (H1, H2 and H3), *Other main roads* (Hø1 and Hø2), and *Local roads.* The handbook presents all the requirements for each road, when they should be used and how they should be designed. The chosen roads for this thesis are Hø1, H1 and H3, which are presented below.

The results from the first research question will be found in the first section 4.1, and they will be used during the main analysis of the physical road infrastructure. The second and third sections of this chapter (4.2 and 4.3) will be the main analysis and result in answers for research question 2 and 3 about what road elements are impacted by AT and TPs, as well as looking at new solutions at some of these troublesome areas.

Roads

H3 is a 4-lane road with a speed limit of 110 km/h. It should be used when there is at least an AADT of 12 000. This is the largest main road. It requires an area of width larger than 23 meters and a very stiff geometric alignment, resulting in a very expensive road, especially in challenging terrain. This is used around high population densities and on the biggest transport arteries, where the transport demand is the highest.

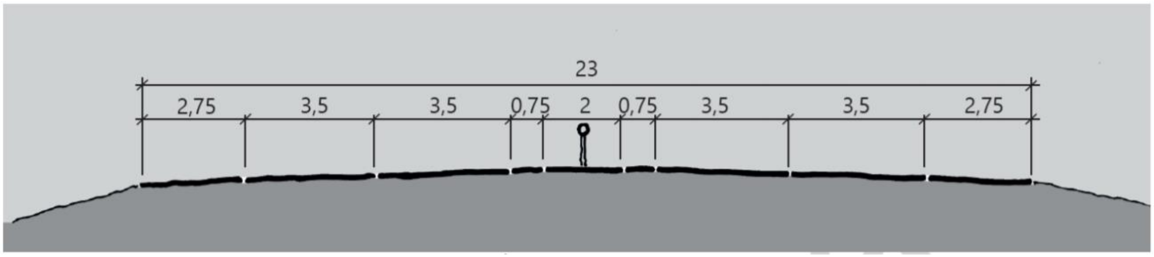

Figure 7. Cross section of H3 (NPRA, 2016a)

[2] The 2018 version of Handbook N100 is currently undergoing approval by the Ministry of Transport. Within this version, there was a large restructuring of road types, reducing the number of road types from previous versions.

H1 is a 2-lane main road and have a speed limit of 80 km/h. It has a capacity below 6 000 AADT and a width of at least 9 meters. With Norway's rather rural landscape, this road type is very common as it makes it possible to build narrower and sharper alignments, reducing the cost of construction in the more difficult Norwegian terrain.

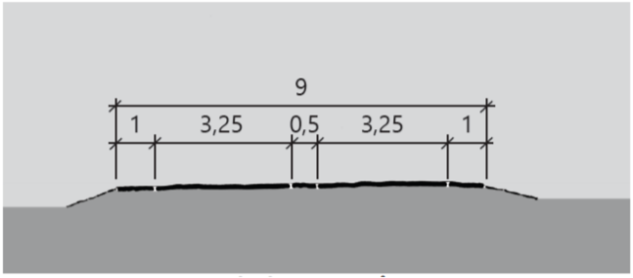

Figure 8. Cross section of H1 (NPRA, 2016a)

Hø1 is a smaller road and is mostly used from the main roads to destinations where traffic volumes are low. It has a capacity below 4 000, speed limit of maximum 80 km/h and requires between 4,5 and 7,5 meters in width. This road type is very common around the coastline areas or around mountainous terrain, where there are small and widespread settlements of people and industries.

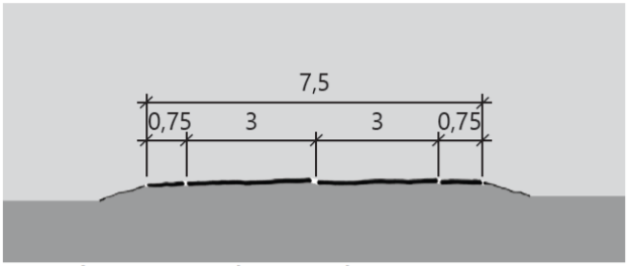

Figure 9. Cross section of Hø1 (NPRA, 2016a)

These roads are representative of the Norwegian road network. H3, H1 and Hø1 will be used in this study when calculating new minimum requirements for stopping sight distances, vertical and horizontal alignments, and other more specific elements such as tunnels, bridges and junctions.

4.1 VEHICLE PERFORMANCE CHARACTERISTICS

This part will examine the differences between conventional trucks, ATs and TPs. First the different design vehicles used today are explained, as this is what is decisive when designing a road. Then ATs will be compared to conventional trucks, before looking at TPs and their differences to a single truck.

Table 5 show the summarized results from the analysis of vehicle performance characteristics, which answers research question 1: What is the differences in vehicle characteristics for conventional trucks vs autonomous trucks? The reason behind the findings will be expanded on below.

Table 5. New concepts vs conventional trucks

What	Conventional truck	Autonomous truck
Reaction time	2 seconds	More reliable times can decrease reaction times for design, as the standard deviation will be smaller if regulated correctly.
Speed	Design speed is based on speed limit with several safety add-ons	Can get rid of safety add-ons, as an AV can be programmed to follow speed limits.
	Truck Platoons	
What	**Single truck**	**Platoon of trucks**
Length	Between 17,5 (semitrailer) and 25,25 meters (modular vehicle combination)	Much longer, but policy related. Due to simultaneously changing lanes of all vehicles, their combined length can cause issues for other drivers and infrastructure.
Weight	Per axle	As the trucks drive so closely, the loading dynamic changes with unknown results.

4.1.1 Design Vehicle

In the latest version of the N100 handbook (2018), main roads are updated to be designed for modular vehicle combinations ("modulvogntog"). For other main roads, they will either be dimensioned for trucks ("vogntog") or modular vehicle combinations, this is chosen at a strategic planning level. Both vehicles are shown in figure 10.

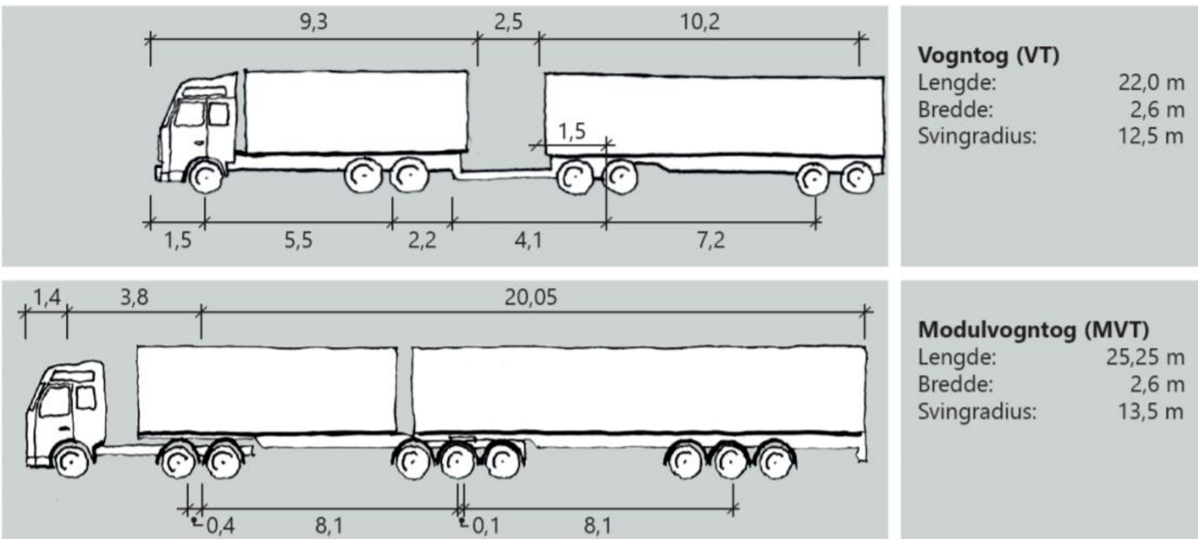

Figure 10. Design vehicles (NPRA, 2016a)

A truck's characteristics are often worse in vehicle performance compared to other types of vehicles, and roads must therefore be designed for these trucks. The modular vehicle combination is a conventional truck driven by a human without any autonomous capabilities, but it has some maximum requirements it must stay within to be legally driven on the few Norwegian roads that are currently supportive of it, including the case study road of E8 in Troms. Length must be no longer than 25,25 meters, width must not be wider than 2,6 meters, and the turning radius cannot be more than 13,5 meters. There is also the aspect of weight, and for modular vehicle combinations the total maximum weight is set to 60 tons. The differences from this vehicle to a truck are mainly the length (22 meters[3]), turning radius (12,5 meters), and the weight restrictions (50 tons). There are exceptions from these requirements, for the likes of timber transport and such, but these are not considered in the analysis.

As the modular vehicle combination is similar to trucks within a truck platoon with its parameters for length and weight, this will be used as the design vehicle for other main roads, as well as main roads. Most demonstrations and tests of truck platoons have been using trucks with lengths between 16 and 19 meters (Ellwanger and Wohlfarth, 2017, Tom Alkim et al., 2016), but modular vehicle combinations are also possible to use (Janssen et al., 2015). The platoon must know all the participating trucks' attributes to self-regulate the necessary distances, as well as acceleration and breaking capabilities. There should therefore not be any problems using a modular vehicle combination in a TP. For the analysis of overtaking lengths, a platoon with modular vehicle combinations will be used as this is the worst-case scenario in terms of lengths.

4.1.2 Single Autonomous Trucks

The interview with a big OEM of automotive vehicles showed that there are numerous possibilities that could be opened with AVs, but that current vehicle regulations do still apply. Compared to today's conventional trucks, the first generation of ATs will only focus on removing the risk that is the human driver. All other aspects will, according to the interviewee, fulfill the necessary vehicle requirements but not likely any more than that. In the future, shapes and dimensions could see new and interesting concepts, the same goes for weight and power ratios, the interviewee stated.

Existing literature does not mention possible changes to trucks in regard to their performance characteristics (e.g. power, turning capabilities and so on), but more of the changes in driving behavior. The driver related parameter of reaction time (also called response time) is something that is expected to change. Fagnant and Kockelman (2015) stated that AVs would introduce faster reaction times, as did Lin et al. (2016), Washburn and Washburn (2018) and Farah et al. (2018). During the interview, the rapid development was mentioned and how newer and better sensors, increased GPU power, and V2X could find solutions completely unknown today. This will also likely decrease the reaction time, however, none of the sources above could give a specific value for this parameter as there are still too many unknowns. A report on off-road AV

[3] Most roads in Norway have a maximum length for trucks set at 19,5 meters unless an exemption is received, but newer roads have been built for trucks with a length of 22 meters, now updated to 25,25 meters.

operation stated that reaction time would be dependent on the complete autonomous system. A system with more sensors and more data that must be processed, will have a longer reaction time compared to a small system with less variables. This also depends on the calculation speeds of the processing unit (Kelly et al., 2006). These processing systems must be onboard, as a cloud-based system will have delays due to transfer times, which can be fatal in certain situations. The specific changes to the reaction time are discussed within the next section.

Other behavior related changes have to do with safety and the much higher awareness compared to humans. Due to the reduction of risk, several sources expect increases to speed, including Hayeri et al. (2015) and U.S. Energy Information Administration (2017). At the same time, higher speeds lead to higher energy consumptions and emissions, something that is currently a hot topic. This will be discussed during the analysis of speed in section 4.2. Washburn and Washburn (2018) stated that due to the faster reaction time and different behavior, design speed could see a modest increase. It is likely that AVs and ATs will impact speed in some way, both speed limit and/or design speed.

Most of the vehicle or performance related parameters are expected to stay unchanged. Power/weight ratios are not set to change drastically due to the implementation of automated technologies, as the trucks must still follow the same guidelines as today. New electric drivetrains or other propulsion systems might introduce new performance characteristics, but this is not confirmed by anyone, and it is not related to AV technology. Some small changes will happen, but the big and expected changes are in form of reaction time and speed changes.

4.1.3 Truck Platoons

The interviewee stated that the difference between a single AT and several ATs connected in a platoon, is that the system needs to consider the state of the whole platoon and all of the different systems and characteristics when actions are calculated. Compared to single trucks, weight restrictions, space on the roadway and visibility are the only additional concerns and issues for platoons, according to the interviewee. Other than that, the interviewee indicated that a TP is not too different from a single AT.

Weight is of specific concern as the trucks are so close to one and another that they function as a single long unit, creating new loading dynamics and distributions that are not yet fully researched (Tom Alkim et al., 2016, Huggins et al., 2017). They also stated that structural constructions might need extra considerations due to these changes in load dynamics. This can be pavement design, barriers, bridges and culverts.

The length of a TP however, seem to be the cause of several problems and have been experienced during some real-life tests, including the 2016 ETPC. The length issue has impacts on overtaking, merging, on/off ramps, difficult traffic conditions and will often result in de-coupling (Tom Alkim et al., 2016). This report also stated that visibility can be an issue, as the lead truck driver must be aware of the whole platoon length when changing lanes, turning etc.

The length can also become a problem when it comes to the perception of the general public, as Janssen et al. (2015) stated in their report. They suggested to only start with a two-truck platoon, so that the public become gradually more aware of the obstacle that several trucks in a platoon could be. The perception is important for implementation of policies and laws to allow TPs.

4.1.4 Conclusion

In this analysis it was uncovered ATs and TPs are most likely to affect two specific basic parameters, reaction time and speed. Reaction time could further impact stopping sight distance and vertical alignment according to figure 5, while speed could influence nearly all design parameters. The expected increase in safety and reliability gained from a AV, will likely allow for a change in the design speed and/or speed limit. The impact of changes to reaction time and speed, and then further to road design parameters, will be discussed in the next section.

TPs will consist of ATs and will therefore have the same differences to conventional trucks as a single AT. Changes caused by the platoon itself are longer lengths and likely a difference in load dynamics.

It is also important to note, based on the OEM interview, that first-generation AVs are being developed to work with existing road design. If they were based on a new type of road design or infrastructure, authorities would likely be less interested in granting these types of vehicles classifications and necessary testing permits, due to the infrastructure changes that would be needed.

4.2 GEOMETRIC ALIGNMENT

This section analyzes the basic parameters used to form geometric requirements for different types of roads. This analysis and discussion are part of research question 2 and 3, where the aim is to find what elements of road design are impacted by ATs and TPs and what solutions that could be feasible.

As described above, reaction time and speed are the basic parameters most likely to change due to the introduction of ATs and TPs. Other notable changes are lengths and loading dynamics caused by TPs. To see how the basic parameter changes would affect parameters within the geometric alignment, stopping sight distance, and vertical and horizontal curve radii, they are calculated using formulas given by V120 and found during the document analysis. These results are presented in tables 6-11, for the three different roads that were selected. These design parameters can be seen as fundamental in the road design, as they, together with gradient, are those parameters which constrict the alignment the most.

As other basic parameters are not expected to be affected by ATs and TPs, they will not be considered within the analysis.

4.2.1 Reaction Time

From answering research question 1, it seems possible the reaction time is getting quicker when using computers instead of a human brain. The interview did not give any proper quantitative answers, neither did the literature. Document analysis revealed that the reaction time parameter is currently set to 2 seconds in Norwegian road design (NPRA, 2014). This time is the sum of everything from identifying the object, understanding what to do, and reacting.

No value for an AVs reaction time has been found within the literature. The interviewee stated that the vehicles will perform as good as humans, therefore this analysis assume the reaction time of first-generation AVs to be around the average human reaction time. A research report on human reaction times while driving found the average to be 0,63 seconds with a standard deviation of 0,07 seconds (Nagler and Nagler, 1973). That average reaction time use the same definition of reaction time as the NPRA for their 2 second constant, making it possible to directly compare them.

When experts state that reaction times will be lowered, they do not reference to the design reaction time, as they do not talk about infrastructure changes but safety and how the vehicle compares to human drivers. This should indicate that there is an acceptance in the field of AVs that reaction times will become lower than the average of humans. The design reaction time for later generations of AVs (around year 2050) is therefore sat to 0,5 seconds and this will be used for further calculations.

Figure 5 show reaction time only has direct influence on stopping sight distance, through the reaction length. The reaction length is how far the vehicle will travel during the full extent of the reaction time. It is therefore only dependent on the speed, V (km/h), and the driver's reaction time, t_r.

$$L_r = t_r \times {}^{V}\!/_{3,6} \quad [m]$$

Using this formula and speed limits in Norway, table 6 show the improvements that is possible to achieve with the assumed reaction times.

Table 6. Reaction lengths

Reaction time	30 km/h	50 km/h	60 km/h	80 km/h	110 km/h
2 seconds	16,7	27,8	33,3	44,4	61,1
0,5 seconds	4,2	6,9	8,3	11,1	15,3

With the reaction time for later generations of AVs sat to 0,5 seconds, it has a possibility to decrease reaction lengths by a massive 75 %. This show how much quicker future vehicles can be, and understandably, they will have a much better and safer obstacle avoidance system compared to today's conventional vehicles.

4.2.2 Speed

Speed Limit

The document analysis showed that the speed is the backbone of road alignment requirements, as this impacts nearly all design parameters, either directly or indirectly (see figure 5). In Norway speed limit varies from 30 to 110 km/h, but the roads themselves are often designed for higher speeds. Due to safety, as unforeseen surface conditions or other factors that could impact a vehicle's performance or driving behavior, safety margins have been added on when designing a road. It is also common that human drivers tend to driver faster than intended, which is why there are speed add-ons for curves with bigger radiuses. As risk, associated with speed and volume, increases, add-on speed increases as well. On roads with high risk, the design speed is over 10 km/h higher than the actual speed limit. This will be expanded on below.

This research concludes with a maximum speed limit on 2-lane roads of 80 km/h instead of 90 km/h, which is the existing standard. Because of heavy vehicles' bad performance characteristics, weight and poor maneuverability, they are not allowed to drive faster than 80 km/h in most European countries, including Norway (Europa.eu, 2018). These factors makes them safety hazards, something that research by Aljanahi et al. (1999) and Glennon (1970) have proven. Trucks are 9 times more likely to involved in accidents when the speed difference between them and other vehicles rise above 15 km/h, and that the deviation from the average speed, and not the speed limit, is the cause of this higher risk. Because of Norway's terrain, there are many slopes which will slow down trucks, easily reaching the 15 km/h differential. Lowering every vehicles speed limit to 80 km/h, the differential will not become too big and the risk for accidents are reduced. This should obviously not be an issue when all vehicles are automated, as the risk element are removed, severely reducing the probability for an accident. But during the many years of mixed traffic, which is unavoidable, this can cause issues. By reducing the speed limit from 90 to 80 km/h, and keeping it even with a full penetration of AVs, other factors are affected. By reducing the speed limit, energy consumption, emissions, noise and wear will be reduced. Especially energy consumption and emissions are important in today's and future world, as mentioned in the introduction chapter.

On the background of these arguments, one should assume a maximum speed limit of 80 km/h on 2-lane roads, as the safety, energy and emission gains are so high and important in today's world. Roads with 4 lanes or more, have good opportunities for overtaking slower vehicles and they are already the safest roads in the Norwegian road system (Tu.no, 2011), so their maximum speed of 110 km/h does not change due to these arguments.

Design Speed

If the expected safety gains from AVs are realized, safety margins and add-ons to speed limits (to determine the design speed) are likely to decrease. The add-on that is supposed to account for humans' tendencies to drive faster in a larger radius curves will disappear as AVs will be programmed to drive at the speed limit. Safety margins are likely to be minimized as well, but not cut completely, as the vehicle can still hit areas of black ice or similar difficult conditions. This would lead to a design speed much closer to the actual speed limit, decreasing the requirements for geometric alignments.

For new roads, this would mean the road would follow the terrain much better, likely reducing construction costs. If the road is to be classified for autonomous driving or platooning, it would have to comply with the new requirements, based of those vehicles. For existing roads, a lower speed limit would mean less need for upgrading the alignment, as the alignment requirements drop with the speed.

There are no quantitative values being stated in the literature surrounding the topic of design speed. The severity of accidents will still be the same, only the probability is reduced. The safety margin is assumed reduced by 30 % due to the expected faster reaction times and smarter behavior, which by some researcher instead has seen as a possibility to increase the design speed (Hayeri et al., 2015). In this research, this was not viewed as a good solution due to the increase in aerodynamic drag and higher energy consumptions needed to keep higher speeds.

Table 7 show how these results affect the safety margin, speed add-on and the total design speed for the three chosen road types. Existing Hø1 are not affected, as it is viewed as safe enough without any additional margins or add-ons, due to its low AADT. This research is only examining the minimum requirements, and speed add-ons are only applied to wider corners. This makes the 30 % reduction in safety margins the only affecting factor.

Table 7. New design speeds

	Hø1	**H1**	**H3**
Safety margin	0	3,5	7
Speed add-on	0	0	0
Design speed	80	83,5	117

4.2.3 Stopping Sight Distance

The stopping sight distance was deemed an important design parameter by Washburn and Washburn (2018), who in their report concluded that the distance is very much dependent on the technology. Currently, they stated, the sensors do not allow for a better view distance than humans or to see through objects. The viewing distance might become better with time, but even without that, this parameter likely to decrease. It is through the calculation formula, given that it is dependent on both speed and reaction time, both of which have been decreased above.

From the document study it was found that this parameter function as both design parameter and minimum requirement (see figure 5). In general, it states the requirements of how far ahead a driver must be able to see, in order to identify obstacles for which the driver needs to stop for. This sight distance is divided into two parts, a reaction length and a breaking length:

1. The reaction length was explained in section 4.2.1. It was there calculated with an assumed reaction time of 0,5 seconds for various Norwegian speed limits.
2. The second part of the equation is the breaking part, how long does it take the vehicle to stop given a specific starting speed. While the first part takes care of the human side, the second part is only about vehicle characteristics. The breaking length can be calculated by this formula:

$$L_b = \frac{V^2}{254{,}3 \times (f_b + s)} \quad [m]$$

   Here V is design speed in km/h, f_b is the breaking friction given by the handbooks, and s is the gradient. Positive or negative slopes will add to or shorten the required breaking distance, but for the calculations a flat terrain is used (s = 0).

Together, reaction and breaking lengths give the stopping sight distance, L_s. As tires are still composed by rubber and the pavement of asphalt or concrete, the friction numbers are very unlikely to change in the nearest future (Washburn and Washburn, 2018). That mean the two major parameters who can influence the required distance are speed and reaction time. As concluded in the speed section of 4.2.2, the speed limit for 2-lane roads are set to a maximum of 80 km/h, this is therefore chosen. With minimized safety margins, the design speed for an 80 km/h speed limit is shown in table 7. The reaction time for AVs of 0,5 seconds was given in section 4.2.1, together with the reaction length.

These numbers make it possible to calculate new minimum requirements for stopping sight distance, shown in table 8. Minimized speed margins takes use of the results from the design speed section above. Reduced reaction time does the same and uses the results from the reaction time section above. Future design is a combination of both minimized speed margins and reduced reaction time.

Table 8. Minimum stopping sight distance

What	Difference	Hø1	H1	H3
Existing design	From N100	105	115	230
Speed	Minimized speed margins	105	110	220
Reaction time	Reduced from 2 to 0,5 sec.	70	80	175
Future design	Reaction time and speed	70	75	165

The results show that a large difference from current road design. Minimizing the speed margins does not have a big influence on the stopping sight distance, only reducing the H3 road with 10 meters, and for H1, the change in design speed was so small that this distance was only reduced by 5 meters. For Hø1, the design speed was unchanged. The reduction in reaction time has a much bigger impact, mostly due to the reaction length being shortened by 75 %. At 110 km/h it is reduced from 61 meters to 15 meters. Adding both minimized speed margins and the reduced reaction time together, the total reduction in stopping sight distance was found, showing an average reduction in stopping sight distance for these three road types of 32 %.

4.2.4 Vertical Curvature

Vertical curves are one of the most decisive parameters for road design, together with horizontal curves and gradients. The document analysis showed that the vertical crest curves are highly dependent on the stopping sight distance, while the sag curves are more dependent on the comfort level of passengers, through vertical acceleration. They are both dependent of the design speed, but only the sag curves are directly impacted. Crest curves are impacted directly by either stopping sight distance or meeting sight distance (dependent on several lanes or 1-lane road), as well as eye height and object height (or vehicle height for the same reason as above). As the human eye are changed to several sensors around the vehicle, there can be possibilities to change the eye height to a higher and more favorable position. But there are currently no laws or policies in the works to enforce a certain minimum height positioning of sensors. And as vehicles comes in different heights, this parameter is assumed to be at the same level as today. The other parameters of vehicle height or object height is not going to change, with no literature mentioning differently. Therefore, speed is the only changing parameter for sag curves and stopping sight distance is the only changing parameter for crest curves.

Crest Curves

The vertical crest radius can be calculated by the given formula:

$$R_{v,min} = \frac{1}{2} \times \left(\frac{L_{s(k)}}{\sqrt{a_1} + \sqrt{a_{2(3)}}} \right) \quad [m]$$

As shown above, the stopping sight distance, L_s, have seen a decrease due to lower design speeds and reaction time. This has an impact on the following crest curves, with its minimum radius decreasing for each road type. The results are shown in table 9.

Table 9. Minimum vertical crest radii

What	Difference	Hø1	H1	H3
Existing design	From N100	2300	2800	11000
Future design	Decreased sight distance	1050	1200	6400

Combined, the results show a decrease in minimum radius of 51 %. This open up new possibilities if a road were to be constructed for AVs only, as their faster reaction time allow for shorter sight distances, impacting the necessary radius of crest curves.

Sag Curves

For sag curves, the radius can be calculated using the following formula:

$$R_{v,min} = \frac{V^2}{12,96 \times a_v} \quad [m]$$

With only small changes to design speed as the only impacting parameter, the changes in radius for sag curves are minimal. The comfort level of passengers is still the most important, as vehicles can keep a much higher speed through such curves than what is deemed comfortable by humans. The results are presented in table 10.

Table 10. Minimum vertical sag radii

What	**Difference**	**Hø1**	**H1**	**H3**
Existing design	From N100	1000	1900	3700
Future design	Decreased design speed	1000	1800	3550

Hø1 does not change its design speed and will therefore not see any changes to any of the influenced design parameters. H1 and H3 show a 5 and 4 % decrease, nothing that will alter the design of a road significantly.

4.2.5 Horizontal Curvature

The horizontal curvature is also impacted by the speed parameter, together with maximum superelevation and cornering friction. Superelevation and cornering friction will stay the same as the speed is not increasing and the rubber and asphalt parameters stay the same, as mentioned in 4.2.3. Thus, as with sag curves, minimum horizontal curves are only affect by the design speed, and its radius can be calculated using this formula:

$$R_{h,min} = \frac{V^2}{127 \times (e_{max} + f_k)} \quad [m]$$

Table 11. Minimum horizontal radii

What	**Difference**	**Hø1**	**H1**	**H3**
Existing design	From N100	225	250	800
Future design	Decreased design speed	215	235	725

The results in table 11, show that the design speed is only slightly altered, with an average decrease of nearly 7 %. This show how much the reaction time is impacting the vertical crest curves. Even if these changes are minimal, it can be used in some extreme cases to cut a few meters off a tunnel or bridge, creating a possibility to save money on construction.

4.2.6 Conclusion

This section examined how ATs and PTs will influence future geometric alignments on the basis of changes in truck characteristics. Changes to reaction time and speed lead to decreased minimum requirements for most design parameters, which showed that stopping sight distance and thus vertical crest curves would see the biggest changes, 75 % and 51 % reduction respectively. Sag curves and horizontal curves only saw some small changes. Based on this, new roads built for AVs only, could by definition be sharper and follow the terrain better. Thus, lowering construction costs.

The NPRA has several recommendations when designing a road, some of which have to do with optimal alignments, esthetics, and optical guidance. They state that wide curves often are desirable, as it contributes to safety and accessibility. They also state that the vertical and horizontal curvature must work together to create a good feel for the drivers, making it easy to keep the correct speed, and that it should be esthetic pleasing as this would keep drivers awake and aware (NPRA, 2014). A repetitiveness straight is very dangerous, as it can lead to sleepiness and increase of average speeds, curvatures are used to counter this. Optical guidance is also very important as it allows drivers to understand the road and how it will continue after a crest curve or horizontal cure. Vegetation and surroundings are great ways of leading the drivers through curves. With the introduction of self-driving vehicles, roads no longer need to lead drivers or constantly curve around to keep the drivers awake. This creates new possibilities for cheaper and more cost-effective roads. They can both have long repetitiveness straights and sharper corners. This can be used to create esthetical pleasing roads seen from a nature point of view, as well as requiring a smaller total length of tunnels or bridges. The recommendations suggested by the NPRA will no longer be necessary and roads can be designed in completely new ways, using efficiency (i.e. travel time) and nature (i.e. esthetics) factors as the most important parameters.

Regarding TPs, it is known from the interview that they will function on any road as long as the road and its elements are strong enough for the forces created by a TP. They will also work on 2-lane roads, as long as the alignment requirements are met. The main issue for TPs seem to be the weight, not the alignment, and a road’s bearing capacity must be able to handle that before it is classified as a platoonable road.

4.3 SPECIFIC ROAD ELEMENTS

From the alignment discussion above, it was clear that the impacted design parameters could be adjusted to both make them feasible and beneficial for ATs and TPs. The differences in vehicle characteristics will likely impact specific road elements too. This section will examine different road elements, such as tunnels and bridges, as well as road related parameters like widths and lengths (i.e. on/off ramps) to answer the research question: Will these road elements be impacted by ATs or TPs and are there any good solutions?

4.3.1 Width

Both literature and interview presented the idea of precise positioning and highly accurate maps. This can be achieved by using very precise sensors, digital maps and location method (Vivacqua et al., 2018, Huggins et al., 2017). As a result, many experts are imaging roads with narrower lanes or even no lanes. They also think about the possibilities of getting extra lanes, maybe dedicated to a specific type of vehicles. This can be achieved by reducing median barriers and widths on all parts of the road (Hayeri et al., 2015).

During ETPC 2016, some drivers mentioned that the reduced widths around roadworks created issues and that too narrow roads could be troublesome (Tom Alkim et al., 2016). They only stated the road were narrower than normal, not mentioning any specific value. However, the interviewee stated the opposite, that TPs can function properly on narrow roads. There is a point where roads become too narrow, increasing the chance it will cause problems for TPs, but this is not yet researched properly.

4-lane Road

Examining the H3 standard and its cross section, it has a minimum width of 23 meters. Each of the 4 lanes are 3,5 meters, with both shoulders taking up 2,75 meters, and the median barrier with shoulders taking a total of 3,5 meters. The cross section can be seen in figure 7. The document analysis of N100 also discovered that in vulnerable or costly terrain, the shoulders can be reduced to 2 meters. The design vehicle for this road is the modular vehicle combination with its width of 2,6 meters. Looking at the narrowest 2-lane road, it has 3-meter wide lanes, and taking this and the truck width into account, that width should work for a 4-lane highway, as that road is also supportive of modular vehicle combinations. By reducing all lanes to this 3 meters and taking 0,5 meters from the inner shoulder, it is possible to fit another lane without compromising the outer shoulder or median barrier, agreeing with research from done by Hayeri et al. (2015). They stated that by reducing the width of each lane and surrounding shoulders, it was possible to fit another lane.

With the reduced risk of accidents, precision driving, and localization, the median barrier could in some instances be in excess of what is necessary for safe operation (Hayeri et al., 2015). This could be reduced to save cross-sectional space, or even removed. The last is not necessary in the case of fitting an extra lane.

The outer shoulders might be the most important areas to withhold. AVs are not any different than other vehicles and will feature errors and mechanical failures, it is important that the vehicles have areas in which they can stop safely without creating dangerous situations or trouble for the traffic flow. Emergency vehicles will still have to pass other vehicles, it is an absolute necessity that there are room for firetrucks to pass, which will require a space of 2,55 meters according to N100. For maintenance vehicles, the outer shoulders are valuable too, as it is a place for them to stop, turn around, plow snow etc. The outer shoulder also plays an important role for the bearing capacity of the road. By introducing heavy TPs to the outskirts of it will have a high possibility to damage the road itself. An occasional emergency vehicle will not create that damage. The outer shoulder should remain in both directions, and it should remain 2,55-2,6 meters if possible, to accommodate for firetrucks to pass stuck traffic in case of an accident.

2-lane Road

The roads of H1 and Hø1 have some differences regarding their widths of lanes and the surrounding sections. This is due to the different traffic volume capacities these roads have.

From the document analysis of N100, it was found that Hø1 has two different cross sections. With lower traffic volumes it is possible to construct this road as a 1-lane road. However, this analysis will only look at the 2-lane road, which have a cross section of 7,5 meters, where each lane is 3 meters with outer shoulders at 0,75 meters. There is no median section. This cross section can be found in figure 9.

H1 has a higher capacity and the cross section is therefore raised to 9 meters, to accommodate 0,25 meters wider lanes and shoulders, with a 0,5-meter median section, as seen in figure 8. This is raising the security along the road. With lower traffic volumes and a placement within a costly and/or vulnerable area, this road could be built to the same specifications as Hø1, with a cross section of 7,5 meters.

These two roads do not have enough cross section to add another lane if existing lane widths are reduced. To make an existing road narrower seem like a waste of resources and will not be discussed further. But, when designing a new road, it is possible to construct this in a narrower fashion, saving money on required material, space, and labor.

To what extent it is smart to make the roads narrower is a decision which need to be made regarding that specific road. However, due to Norway's, and many other northern countries, harsh winter climate, narrower roads might not be the best solution. Icy and slippery roads with snow on both sides takes away much of the safety margin that is present on today's roads. During the dark winter periods, animals tend to cross roads as they present easy access to the other side, with little to no snow in their way. The ability for a conventional vehicle to swerve to avoid hitting an animal is important, and it will not be any different for an AV, even if it should be able to see the animal better in the dark and react faster.

Conclusion

Based on the precision driving executed by AVs, and subsequently by ATs and TPs, road widths could be made narrower. As modular vehicle combinations can have a maximum width of 2,6 meters, the widest possible vehicle allowed to drive on Norwegian roads, the 3 meters width used by Hø1 roads should be sufficient for trucks when precision driving is implemented. With no values for lane widths at the roadworks site met during ETPC 2016, one must assume that 3 meters is enough as it is currently used on 80 km/h 2-lane roads.

For a 4-lane road, this mean it will be possible to get a fifth lane. If this is something that could be used for better efficiency, it should be considered. Shoulders should stay the same to allow emergency vehicles to pass and to keep the bearing capacity, but median barriers could possibly be reduced due to the lower probability of accidents.

Upgrading roads will really only apply to 4-lane roads, for the reasons above. As 2-lane roads cannot get a third lane, there is no reason to use resources to narrow the roads. This minimum requirement would therefore be used when designing and constructing new roads, as it can lead to less space and materials needed, offering cheaper roads.

4.3.2 Tunnels

Tunnels are very important for Norway's transport system, due to the natural terrain, with its coastline, fjords and mountains. An interactive map by the NPRA with all road elements attached, show that there are currently 1189 tunnels in Norway, with the majority located around the coastal areas (Vegvesen.no, 2018). Any necessary changes to make these tunnels supportive of ATs or TPs could become very expensive, as upgrading tunnels cost the same as building new (Tu.no, 2013). As a consequence of big costs and Norway's sparse population in large parts of the country, upgrading tunnels might not be cost-effective.

The literature review showed several real-life tests in urban areas and on high-quality highways were tunnels had been traversed without issues. A project in Parma, called PROUD, showed that an AV could drive the whole stretch of a total of 8 tunnels with traffic without problems (Broggi et al., 2015). During the 2016 ETPC, truck manufacturers said that driving through short tunnels would not make any systems fail, but any tunnels longer than 200 meters could be a potential threat. They were also asked to de-couple through tunnels in Belgium as the authorities did not deem the technology safe enough (Tom Alkim et al., 2016). During the tests within the ETPC, tunnels did not cause any problems for the trucks, drivers or surrounding traffic.

The document analysis found that Norwegian tunnels should not be built with more than a 5 % gradient, and if it is over 3 %, safety measures must be fitted appropriately (e.g. overtaking lanes). However, many of Norway's tunnels are the opposite in terms of quality, safety and space compared to the where AVs and TPs have been tested. There are several undersea tunnels, and these tend to have excessively steep gradients, like the "Maursund" undersea tunnel in Troms. Gradients on both sides reach a maximum of 10 % with a road width of only 5,96 meters. Tunnels like this are common, and only around 1 kilometer further up the same road there is

Figure 11. Maursund undersea tunnel (Skog, 2017)

a second mountain tunnel, “Kågentunnelen”. This has not the gradient problems, but it is very low and several trucks have hit the ceiling when meeting other trucks. Like many other roads, this does not have much traffic, but along the road there is a big fish farm, which in 2016 generated 25 trucks a day with fresh fish (Antonsen and Rostad, 2016). Another undersea tunnel that does feature overtaking lanes and a much higher standard due to higher traffic volumes, is the “Oslofjordtunnelen” just south of Oslo. This tunnel show that even high-quality tunnels can have massive issues due to too steep slopes. With its AADT of 7500 it has a slope of 7 % for a very long distance in both directions. This have made it prone to truck fires and other incidents. Closures are common and costing the society a lot of resources. From 2011 to June of 2017 there were 11 fires, from 2013 to May of 2017 there were 741 closures of the tunnel, for total of 1860 hours (Vegvesen.no, 2017b). This show that even though a tunnel is of high quality and part of a main road, slopes might create massive issue even if the tunnels are built satisfactory in regard to the standards.

These tunnels are examples of Norway’s big issue. If many of the Norwegian tunnels are not supportive of ATs or TPs, what would be the necessary action to make and how expensive would it be? These examples also show that the research conducted in urban or highway tunnels, are difficult to relate to for many of Norway’s tunnels. More research must be done on this matter, finding out how the different types of tunnels, located on important transport arteries in Norway, will cope with these new truck concepts.

For Norway’s highway tunnels, it seems that smaller infrastructure upgrades might be enough. The problem with tunnels that are longer than 200 meters, is that the GNSS signal is lost for too long. The interviewee stated that accurate positioning systems are a must, and that in tunnels or similar areas (e.g. high-density areas with high-rises), it is problematic when it does not work. He suggested that V2I communication would certainly improve the current situation in these areas. And there are several solutions currently under research for issues like this. One example uses lights, image sensor and V2I to precisely locate the vehicle with an approximately error of 1 meter, and another example use Cooperative Localization (CLoc) and a sensor fusion with V2V and V2I to determine the vehicle’s position based on neighbor vehicles whenever GNSS fails (Kim and Jung, 2016, Hoang et al., 2017).

Technical requirements

For highway tunnels, the standard is often very high, and it should not present a huge problem in terms of alignment and space. However, for the lower quality roads with small numbers of AADT, this might become an issue.

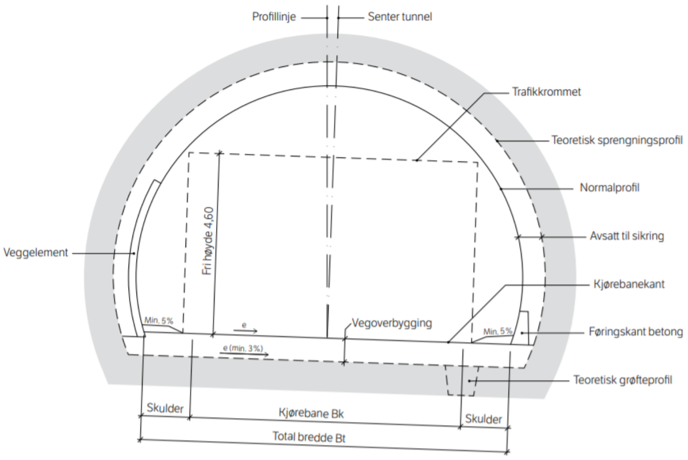

Figure 12. Schematic tunnel profile (NPRA, 2016b)

In the N100 it is stated a tunnel profile for each road type, a schematic tunnel profile is shown in figure 6. H3 must use two separate tunnels for its 4 lanes, both being T10,5 tunnels, which do not present any problems for trucks. H1 must use T9,5 with strengthened road markings. For Hø1 roads, tunnels should also be of the type T9,5. With lower traffic volumes, T8,5 could be used, as long as the safety is satisfactory. These tunnels are described more in the handbook for tunnels, N500.

The tunnels must obey the same requirements of alignments as other parts of the road. Tunnels shorter than 500 meters should also have the same cross section as the connecting road. For horizontal curves, it is important that not only the minimum radius is met, but also as an extra requirement, the stopping sight distance. Due to the close proximity of tunnel walls, as seen in figure 12, this parameter is a must to check. This secondary requirement is calculated using the following formula:

$$R_{min} = \frac{L_s^2}{8 \times B} \quad [m]$$

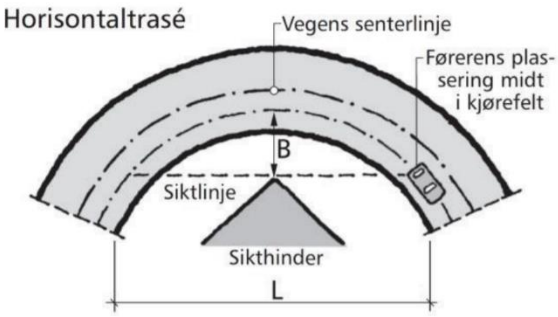

Figure 13. Sight line and hindrance (NPRA, 2014)

B represents the distance from the middle of the lane to the tunnel wall as shown in figure 13. L_s is the stopping sight distance. This distanced could be viewed as the horizontal sight distance as well. For AVs, this minimum radius requirement will become easier to achieve, due to the faster reaction time, as shown in the sections above.

<u>Conclusion</u>

With accurate positioning inside of tunnels achieved by using connectivity among other technologies, lanes can be as narrow as for the rest of the road network. This mean that tunnel walls will be very close and hinder the sight distances in horizontal curves. For lower quality tunnels, this might become an issue, and something that would require either an upgrade to the alignment or a brand-new tunnel. As both options are equally expensive, it might become problematic if this issue concerns many Norwegian tunnels.

With the narrow lanes, the tunnel profile must ensure that there is enough free height for trucks. Creating round tunnel profiles might need to be changed to rectangular to overcome such issues as seen in the “Kågentunnelen”.

Digital infrastructure seems to be very important for tunnels longer than 200 meters, and implementation of this should see more research for Norwegian conditions.

Slopes in tunnels have been a huge issue for trucks in Norway, especially in the more expensive undersea tunnels. If this can be improved by ATs or if upgrades are needed, must be researched further. Research done by other countries cannot relate to this issue and must therefore not be used in further research of these types of tunnels.

4.3.3 Bridges

The literature describe that bridges can present a problem for TPs. Several sources states that the load dynamics created by a TP might be different than for a conventional truck (Huggins et al., 2017, Janssen et al., 2015). The weight is what is most likely to cause problems, as each span must be able to handle more weight than before as more trucks are able to fit on a smaller space. Some other factors include more wear on pavement and bridge elements due to new and different load dynamics and that today's railings are too weak to withstand a crash by several trucks (Huggins et al., 2017).

In Norway, because of the same factors as with tunnels, there are a lot of bridges. From the NRDB, it can be found that there are currently nearly 10 500 bridges in Norway that are longer than 10 meters (Vegvesen.no, 2018). They are also of varying quality, again due to many of the same factors as with tunnels; low AADT, spread population and so on. This varying quality was recently discovered by Norwegian media, who found that as many as 1000 bridges had been neglected and were in critical conditions (Nilsen et al., 2017). These bridges had lost bearing capacity, as well as decreased life span. Because of the additional forces created by TPs, weaker and damaged bridges like these could be a major threat towards implementation of TPs.

While there is limited literature on the impact TPs' create on bridges, other and similar situations can be considered. One of which are timber trucks in northern Sweden and Finland, which present some of the same road and weather conditions as in Norway. In these countries, huge modular vehicle combinations have in the last couple of years been tested, weighing 90 (Sweden) and 104 (Finland) tons. The Swedish trucks are 30 meters long, but as there are more axels, the axel load is less than for the existing timber truck of 60 tons. Examining the roads after two years of use, no additional wear on the

Figure 14. Swedish 90-ton timber truck (Löfroth and Svenson, 2010)

road was found. Bridges could handle the extra weight as long as some precautions was taken, meaning that some bridges with longer spans had to be reinforced (Löfroth and Svenson, 2010). In Finland, the 33-meter long and 104-ton timber truck made some bridges signalized as there were uncertainties if the bridge could cope with several vehicles at the same time. The lights could be controlled by the driver in the timber truck (Mäntyranta, 2015). These examples both show that there are concerns and that action has to be taken when heavier trucks are introduced, which confirms the assumptions made by earlier literature, that longer spans could be impacted by TPs. Although TPs and these timber truck examples are not the same, they both have increased weight on a shorter distance, impacting bridges in a similar way. Until further research is conducted, this is pointing in a direction that concludes that the larger weight might need reinforced bridges.

Railing is another concern for TPs, as Huggins et al. (2017) mention in their report, protective barriers are made to handle certain forces, but that design might not be strong enough for a 2, 3 or bigger TP with nearly no headway. The railings are most often constructed to catch one vehicle, not several. Although accidents are expected to be rare, they might happen and in that case the barriers must be able to withstand the extra forces. The document analysis showed that the handbook V161 is used to show where different barriers are used. Some areas are more important and must have stronger barriers than others, often where the consequences or risks are greater. This could be surrounding bridge pillars, bridges spanning highspeed railways or at large cliffsides. The design of barriers is dependent on more research.

Conclusion

As forces and weights seem to be the big issues surrounding bridges and railings, a single AT is of no concern for these elements. TPs however, with its much higher weight, different load dynamics and in case of an accident, much higher forces, can become issues for these elements. Research on this topic is very limited and when testing platoons in real-life, the trucks have previously de-coupled and increased the gap as a result of this uncertainty (Tom Alkim et al., 2016).

For Norway, this is a major concern as the country feature a lot of bridges in all sizes and forms. And as Norwegian media found, the quality control of these bridges is very bad and cannot be viewed as safe for any heavy vehicle. Bridges must see a lot of research before the consequences of TPs can be fully understood. However, implementation of modular vehicles combinations in Norway and high-capacity timber trucks in Sweden and Finland might generate more understanding and some answers, something that should be closely monitored in the future.

4.3.4 Junctions

Junctions are complex traffic situations, and according to the interviewee and Maarseveen et al. (2017), they can be some of the most difficult elements to traverse for a platoon, especially on/off ramps. These elements present a high risk of de-coupling, and subsequently problems connecting again, creating risk and wasting resources and time. This was also found during the 2016 ETPC, where truck drivers stated that it was difficult to merge a whole platoon as they change lanes simultaneously (Tom Alkim et al., 2016).

Junctions are divided into two categories, interchanges and intersections. The big difference being that interchanges are two roads, usually highways, passing over and under each other, while intersections meet at the same level. Interchanges use ramps to connect the roads and can include designs such as cloverleafs and dumbbells (shown in figure 15). Intersections usually use a set of rules or a system (e.g. traffic lights) to dictate the traffic flow and avoiding crossing paths. Designs include roundabouts, X and T-junctions, which can be signalized and not.

For AVs, problems occur in these environments as the traffic situations are so complex and there are a large number of objects to track, especially at intersections. At interchanges, high speeds and limited range on sensors can cause issues. The literature mostly refers to digital infrastructure and how V2V and V2I can fix these issues (Hayeri et al., 2015). Solutions for both types of junction are under research and will mostly require connectivity and only minimal adjustments to the physical infrastructure.

Interchanges

This element usually uses ramps, as described above and can be seen in figure 15. This leads to the process of merging, which is the big problem, especially for TPs due to their length. The range limitations of most sensors cause AVs to have a limited perception range (Maarseveen et al., 2017). The suggested solution is to use what is called *Cooperative Perception*, meaning vehicles communicate with each other and thereby extend their perception range beyond the range of what the sensors are capable of. With the extra range and communication, the vehicles can work together to create the most optimized traffic flow through the merging process.

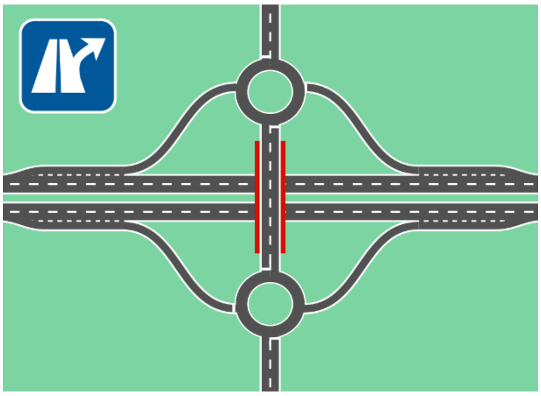

Figure 15. Dumbbell interchange (Haase, 2013)

Even with this optimized process, TPs will cause issues during higher traffic intensities. Simulation results show that both two and three-truck platoons will cause issue, although three trucks are much worse (Maarseveen et al., 2017). This research recommends that platooning is not allowed during certain times, like peak hours. This result corresponds to the findings during the 2016 ETPC, where drivers had to de-coupled during interchanges, and then merge together on the highway. This could create dangerous situations as the front trucks would have to slow down and the process of reconnecting takes between 30 to 60 seconds (Tom Alkim et al., 2016).

Due to this, other vehicles, including trucks, would try overtaking the platoon, and it would see an increased possibility of cars getting between the trucks part of the platoon.

The truck drivers also said that they felt longer on-ramps could help the process of reconnecting and merging, as other vehicles had time to adapt and create the necessary space needed to move the whole platoon as one unit. This would obviously be easier on a 4-lane road than on a 2-lane road, as vehicles can move to the other lane.

<u>Intersection</u>

With several moving vehicles and interaction with pedestrians and cyclists, as seen in figure 16, the traffic situation requires AVs to track a large number of objects. New ideas to improve these bottlenecks are becoming possible due to the new connectivity technologies. Simulations have shown great results when V2V, V2I or V2X communication are used. An autonomous slot-based system would in an X-junction cut delays from 99 seconds to 2,5 seconds for each vehicle, if that junction went from signalized to slot-based and vehicles arrived every 2 seconds from each direction (Ackerman, 2016). These systems will require all vehicle to be autonomous and connected. And the simulations do not seem to consider ATs or TPs either, which is something that should definitely be considered as these would block the system more than a normal car. Another obvious issue with a solution like this, is the presence of cyclists and pedestrians, who cannot be part of such intersections. There would need to be a separate infrastructure for the soft users, either using tunnels or bridges to cross the road.

Figure 16. Intersection in Makati City, Philippines (Gonzalez, 2006)

If these simulation results can be reproduced with real-life tests, it shows that the efficiency of intersections can be substantially improved. It also shows that roundabouts should be remade into X or T-junctions as these are more suited for this slot-based system. This corresponds well to findings from the document analysis. The updated handbook N100 states that the use of roundabouts should be restricted and minimized. This would help the efficiency of an autonomous slot-based system, but also help TPs cross intersections. Roundabouts are not constructed to support TPs, and although it could work if other vehicles yield, an X-junction is easier to cross for trucks in general.

Conclusion

Junctions seem to be very dependent on connectivity technologies to increase their future throughput. It can help increase the perception range of limited sensors and help place vehicles on the most effective slot. There are clearly issues with TPs at ramps and merging processes, something that should definitely be researched further. Autonomous slot-based system must research the use of ATs and TPs as well, as these are much bigger influences on the traffic flow than smaller cars.

Necessary physical infrastructure changes as a result of implementing the above solutions are to construct standalone infrastructures for pedestrians and cyclists, so they can cross junctions without interrupting the traffic flow, change roundabouts to X or T-junctions, and increase the length of on-ramps to help platoons merge.

4.3.5 Overtaking Lanes

Overtaking lanes have in the past been designed based on biggest design vehicles, which were trucks with a maximum length of 22 meters. But in the 2018 update this has changed to the modular vehicle combination for all roads, and thereby a 15 % increase in design vehicle length to 25,25 meters. The existing minimum length of overtaking lanes on 800 meters will likely be too short for this 15 % increase, but with the introduction of TPs, this vehicle length will increase by a substantially larger amount. This raise the question of how long overtaking lanes must be to allow other vehicles to overtake TP? And due to AVs driving at speed limits, will there be necessary with overtaking lanes at all?

By definition, AVs will drive with a good behavior and at speed limits, not taking risky overtakes or other maneuvers. With the assumption of a maximum speed limit of 80 km/h for all 2-lane roads from the speed section 4.2.2, all vehicles will drive at the same speed, and the average speed will be very close to the speed limit. The only reason for an overtaking lane is if there are deviations from the average speed or if the average speed is very low. The only place this should happen, when only AVs are present, is in slopes, where trucks cannot keep the same speed. As explained in the speed section, deviation from the average speed is the issue, and 15 km/h difference was then found to be the critical point. This is confirmed by handbook V120, as this is the critical speed for creating overtaking lanes in slopes for most roads.

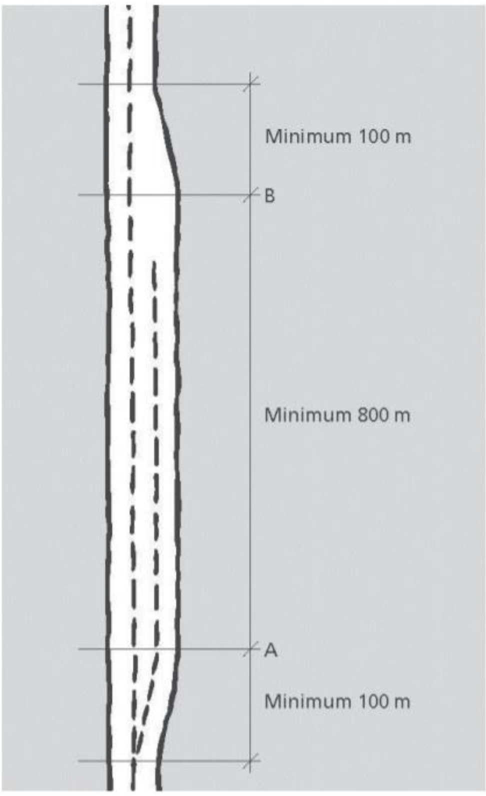

Figure 17. Existing minimum lengths for overtaking lanes (NPRA, 2014)

Further analysis will assume overtaking lanes are only necessary in slopes when AVs are the only vehicles present. How will the introduction of TPs impact the necessary overtaking lane length?

The document analysis of V120 showed that existing overtaking lanes are minimum 800 meters long, with 100 meters of increasing width at each end (figure 17). The necessary overtaking lane lengths are calculated using a computer model which uses parameters as speed, gradient, critical speed (difference between vehicles), length of slope and percentage of heavy vehicles. It bases its calculations on the design vehicle for that specific road, which now is changed to modular vehicle combinations.

Calculations in this research has been somewhat simplified compared to the computer model. It uses a speed limit of 80 km/h and differential speeds of 15 and 20 km/h as these are critical speeds according to V120. AVs can drive faster than the speed limit when its necessary (Ingrassia, 2014), but as the Norwegian computer model assumes the overtaking vehicles are driving at the speed limit, this is assumed in this calculation as well. Any higher differential speeds will only reduce the overtaking distances, but this is calculating minimum lengths and a worst-case scenario must therefore be used. This worst-case scenario includes the use of only modular vehicle combinations in the platoon, as this will be the maximum length of any possible platoon in Norway. The calculation also take use of Janssen et al. (2015)'s platooning gap of 0,3 seconds at that speed.

Table 12 show the results and compare them to a reference truck of 22 meters. This reference truck is the old standard which existing roads should satisfy. The calculations are done in Excel and is done by dividing the speed difference (15 or 20 km/h) on the total length of the platoon, and then multiplying it with the speed which the overtaking vehicles drive at (80 km/h).

Table 12. Overtaking distances

Numbers of trucks	**Total length (front to back)**	**Overtaking distance (15 km/h difference)**	**Overtaking distance (20 km/h difference)**
Reference truck	22	117,33	88,00
1	25,25	134,67	101,00
2	57,17	304,89	228,67
3	89,08	475,11	356,33
4	121	645,33	484,00
5	152,92	815,56	611,67

Limitations with this calculation include the unrealistic constant speed of trucks and that no distances are added on the back or front of the platoon. The overtaking distance only says how much space is required to pass the length of the platoon, with the gaps between each truck. In real-life the overtaking vehicle would start further behind the TP and then end in front of it, so it will require additional distance to what is proposed in the table above.

Conclusion

Janssen et al. (2015) suggested to start with a two-truck platoon, and as people get used to the idea, this could be increased to three trucks. A worst-case scenario show that the overtaking distance will increase with 160 % with a two-truck platoon, compared to what the overtaking lanes are based on today. A three-truck platoon will increase the overtaking distance by 300 % compared to the reference truck. This clearly show that the minimum lengths for overtaking lanes of 800 meters are way to short and must be updated to correspond to the concept of TPs. A TP with 5 trucks require a distance that is longer than today's minimum requirement, this shows that an implementation of so long TPs might become too challenging in terms of overtaking. Other possible solutions will be discussed in the discussion chapter below.

5 Case Study

The objective of this case study is to examine the possibilities for Norwegian rural main roads to become supportive of ATs and PTs with the use of the requirements presented during the analysis. The question is how much will a common road be impacted and what are the consequences of introducing these new types of vehicles in the far future? While the case study specifically examines one road, the results are meant to be usable for all roads of a similar characteristic. The requirements set in the method chapter for what road to choose is therefore very important to reach a wide spectrum of roads in Norway.

The results will show how much of the existing road that must be upgraded from today's standard to meet with the new requirements. The specific factors that are used in this study are horizontal curvature, vertical curvature and width, all of which are of importance for ATs and TPs but that is also impacted by the new technology.

In the first section the stretch of road will be introduced and discussed against the requirements set in the method chapter. Then the results will be presented with some additional comments. The procedure for this small case study can be found in the method chapter.

5.1 Case Stretch

The requirements set in the method chapter were a tool to find a common Norwegian rural road which would represent the tough terrain and conditions found many places in Norway. The requirements are listed below:

- 2-lane road
- An older road
- Tough Norwegian terrain and harsh weather conditions
- Big or important transport artery

During the literature review and other connections, a road in Troms were found, E8, meeting all the requirements. The 38-km long road is located between Skibotn and Kilpisjärvi at the Finnish border and is a test stretch for an ITS project held by the NPRA. The project started in 2018 and it is testing different measure technologies to find what is best suited for the difficult conditions of Norwegian roads. While this project is conducted with the help of trucks and with the purpose to better the efficiency and safety for these trucks, platooning has been tested out as well. This could provide the research with extra data, beside the extra documentation and maps from their ITS project (Vegvesen.no, 2017a).

The stretch consists of 2 lanes, sharp corners, narrow widths and steep climbs as it navigates its way through a valley towards a mountain plateau and the Finnish border. With its relative low AADT of 700 vehicles in 2017, safety measures are few and the widths are small (Vegvesen.no, 2018). With speed limits ranging between 80 and 90 km/h, the possibilities for accidents are higher than for bigger and better roads. This is very typical for Norway, as the population is very spread and it is too expensive to have a good standard on all roads. Some small parts of the road are of newer quality and follow the current standard and requirements, but most of the stretch is of an older generation.

As the road traverse through a valley and up on a mountain far beyond the arctic circle, the weather conditions can become very though, especially during the winter. The road is very exposed to the elements and with several steep climbs, trucks are often seen to get stuck and interrupting the traffic flow. This is one of the main reasons why the NPRA choose this stretch for its ITS project.

This specific stretch is of high importance as it is the one of the biggest transport arteries of Norway's second biggest export, fresh fish, to the Asian market (Worldstopexports.com, 2018). As this export is very sensitive and must be transported within a certain timeframe, research to improve the transportation is common, this includes the ITS project. The introduction of ATs, and even TPs, can further increase efficiency and safety, and thus decrease downtime and road closures. The fish on this stretch is driven on trucks from the fish farms to Helsinki and then put on flights to Asia, where they will be at their destination within 36 hours,

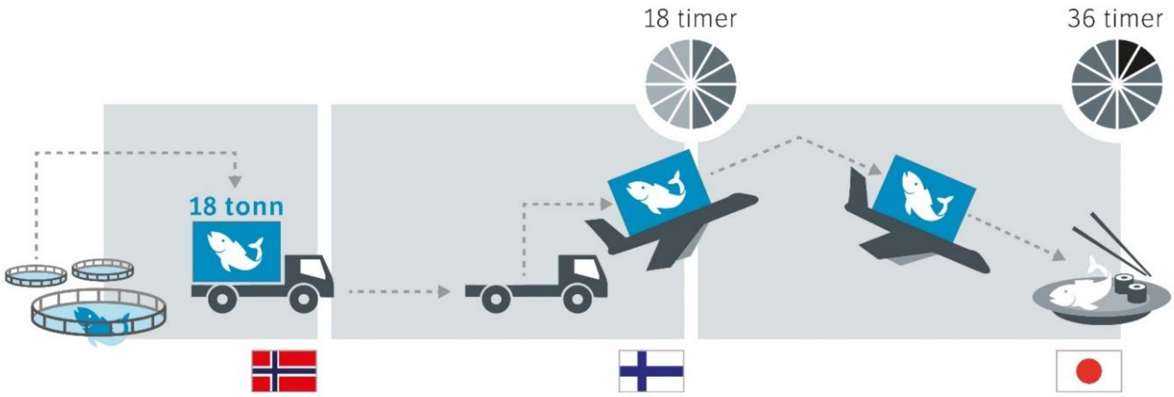

Figure 18. Fresh fish transport between Norway and Japan (NPRA, 2017)

see figure 18.

In 2013, the road was used to transport 22 412 tons of fresh salmon and trout, totaling 2,5 % of the grand total exported that year (Hanssen et al., 2014). Olafsen et al. (2012)'s report on salmon and trout export concluded with a massive expected growth, reaching 5 million tons by 2050. As there are several exporting transport arteries, just like this road, they will all need to be able to handle a higher amount of transportation. In 2017 exported salmon had increased to over 1 million tons (64,7 billion NOK), nearly a doubling from 2013 and showed that Olafsen et al. (2012)'s conclusion could seem to be correct. It is fair to assume that the numbers for all the different roads used for exported fresh fish have increased and the number of trucks will keep increasing as the demand for Norwegian fish rise further.

E8, specifically, saw an AADT of 700 vehicles in 2017 with 26 % of those being heavy vehicles (182 heavy vehicles on an average day). Based on the safety concerns regarding trucks in climbs, as concluded by Glennon (1970) and (Aljanahi et al., 1999) and the importance of efficiency regarding fresh fish export, this road can benefit greatly from the suggested benefits of ATs and TPs[4].

The stretch of road between Skibotn and Kilpisjärvi seem to meet all requirements and will be used to show how the road design requirements found during the analysis can impact existing roads.

5.2 Results

Using the requirements from the prior analysis and adding them onto the E8 in Troms, shows how an existing and common Norwegian road would be impacted when it must become supportive of ATs and TPs.

Due to the low AADT of this road, this would be a Hø1 road as it supports less than 4000 AADT. The minimum requirements for that road type are:

Table 13. New minimum requirements for an Hø1 road

Crest curve	Sag curve	Horizontal curve	Total driving lanes width	Total asphalt-covered width
1050 meters	-1000 meters	± 225 meters	6 meters (2 lanes x 3 meters)	6,4 meters

As mentioned in the method chapter, the used data is an approximation of the road found through a survey of the road. A regression of that data to give the best possible description of the geometry. This is the best data there is, as the technical drawings are no longer available, but it is just an approximation and the results should not be considered to be fully correct. To counter for any variation from the analytical data or from the dataset, the road will also be checked for minimum requirements approximately 10 % higher and lower than those found during the analysis.

Alignment

To find out if the vertical and horizontal curves of E8 are within the minimum requirements, Excel was used to find how many meters that did not comply with the requirements shown in table 13. Table 14 present the total length of each element that do not fulfill the minimum requirements. Each length is in meters.

[4] If a platoon with fresh fish get stuck due to a road closure, the costs of lost fish will be greater than if there were only one and one truck. However, due to all the measurements of ITS and other technologies on the road, this occurrence is assumed to be minimized.

Table 14. Results from the case study

	Vertical curvature	Horizontal curvature	Total driving lanes width	Total asphalt-covered width
Requirements from table 13	700	1632	8264	3257
10 % higher requirements	865	1919		
10 % lower requirements	408	1282		

The element that need the least upgrades is the vertical curvature, with only 700 meters of the 38-km road that do not meet the requirements. This equals a 1,83 % of the total road length. A total of 11 680 meters did not fulfill the standard of 1050 or -1000 radii, but of those, 10 980 meters were straights (0-meter radius).

With 10 % higher requirements, the crest curve gets a radius of 1 155 meters and the sag curve gets a radius of -1 100 meters. This increase the length of needed upgrades to 865 meters (2,26 %). With 10 % lower requirements, the crest curve gets a radius of 945 meters and the sag curve gets a radius of -900 meters. This decrease the length to 408 meters (1,06 %). This shows that the results are conclusive, and even with a margin of error, the results are within the same area.

For the horizontal curvature, the requirement is the same in the future. This was due to the relative little change in speed limits, as this was the only influencing parameter. Accordingly, this case study of the E8 stretch will show how well the road follow both existing and future requirements. It was found to consist of 17 637 meters of curves, just under half of the 38-km road. Of this, a total of 1 632 meters were not within the limits set by the minimum requirements. A total of 4,24 % of the road is either in need for upgrades or lower speed limits.

To check the result with a 10 % margin of error, like with the vertical curves, the minimum requirements changed to ± 248 and ± 202 meters. The increase gives 1919 meters in need of upgrades (4,98 %) and the decrease gives 1282 meters (3,33 %). Again, the results seem to be accurate.

The results show that parts of the road are not even following current requirements, and this is because it was built a long time ago with very different standards. These calculations were also done with a speed limit of 80 km/h, due to assumptions made in the speed section (4.2.2). But currently, this road has sections with 90 km/h speed limits, making these upgrading lengths possibly longer as that speed has higher requirements. This can obviously cause issues, as too high speeds in too sharp corners can result in accidents due to loss of friction. But, this is currently not a massive problem, as shown by the lack of upgrades done with this and many similar roads. Human drivers can easily adjust their speed, and the requirements have some safety measures added to help with issues like this. For AVs, this might be different, but there is currently very little information on the subject. One might think that the machine learning part and connectivity will share the vehicles' perception of the road and make following vehicles adjust their speed at specific corners. A test with a three-truck platoon have already been conducted on the road, driving at 80 km/h, it did not encounter any issues. It is important to note that TPs are currently being driven from the lead truck, making it possible to adjust their speed as seen necessary, but when totally driverless trucks and platoons arrive, this issue must have been solved. There are so many roads in the world with different requirements and many of those do not follow their own requirements. Upgrading roads' alignments can be as expensive as building a new road, and in Norway this could be between 50 – 90 000 NOK per meter for a road of this size (Vegvesen.no).

Widths

To find how much of the road is within the requirements of lane width, the same method as above was used. For this parameter the dataset contained both total driving-lane width and total asphalt-covered width, and both will therefore be tested. Some of the road has been upgraded to a newer standard, and its width data was not present in the database. The length for this parameter was therefore 8 km shorter (30 900 meters).

As this road is old, the width requirement can sometimes be difficult to accomplish. This analysis found a total of 8264 meters having total driving-lane widths less than 2x3 meters (6 meters). This is 26,7 % of the total length, and a much bigger part of the road than any of the alignment parameters. But, as the lane width can vary in corners and other factors, the analysis also checked for the total asphalt-covered width, where the requirement was set to 6 meters of lanes and 0,2 meters of asphalted shoulders on each side, totaling a requirement of 6,4 meters. This time, only 10,5 % of the road were narrower than the minimum requirements (3257 meters).

This parameter is difficult as it varies on large portions of the road, and this causes some limitations. The data provided was segmented into approximately 500 meter-lengths, averaging 490 meters due to some much smaller segments. Over those 500 meters, the width can vary a lot, and this will add to the uncertainty of the result. Secondly, the width will vary with corners, if widening is needed. The requirements do not take this into account and should only be used on straights. But this road is full of corners, as seen during the horizontal results, nearly 50 % of the road consists of corners. These corners can be widened to some degree and will therefore help the result. It is likely that the road would require more upgrades than what these results show.

6 Discussion

In this chapter, the results presented in chapter 4 will be discussed, with the goal to answer the main objective of this thesis. Using the research questions, a discussion surrounding the given topic will be used to conclude the research conducted in this thesis. That conclusion follows in the next chapter.

The main objective of this research was:

How will the road design be affected by the use of autonomous and connected trucks in 2050?

The research questions used to answer this was:

1. What is the differences in vehicle characteristics for conventional trucks vs autonomous trucks?
2. What elements of road design are impacted by autonomous trucks and/or truck platoons?
3. How can these elements be improved to be supportive of autonomous trucks and truck platoons?

The first section of this chapter will discuss the results and its implications. The second chapter will discuss the weaknesses and limitations of this research, with the last chapter discussing future research on the field.

6.1 Implications of results

This section examines the results under each research question and discuss their implications on the future physical infrastructure. Research question 2 and 3 are tightly connected and will be discussed together.

6.1.1 What is the differences in vehicle characteristics for conventional trucks vs autonomous trucks?

During the interview, the interviewee stated that the first-generation of AVs will only focus on removing the driver. Other vehicle parameters will fulfill the necessary requirements, but nothing more. This implies that the first-generations will just remove the risk that a human driver contributes with, and all other parameters and factors will stay the same as for conventional vehicles.

The removal of risk, created or taken by human drivers, will lead to a reduction of accidents, as 90 % of all serious accidents are caused by human errors. Removing issues like sleepiness and drink driving, will mean a lower accident rate for everyone on or by a road. Also, the ability to drive at the speed limits will have an impact on the road design as there are no longer need for speed add-ons. This will be discussed further in the section below, but as the document analysis showed, speed influence nearly all road design parameters. Another factor that is removed as a result of removing the human driver, is the need to creating stimulating roads. To help drivers keep within the speed limit, stay awake, and be aware, roads follow the terrain with corners that are created in such a way that the speed limit feels like the natural speed to drive at. Not using long straights for lengthy periods of time, ensures that the driver stays alert and that he does not get sleepy due to the repetitiveness of a straight. Although this is not a parameter in itself, AVs will have an impact on the way roads are and can be designed, opening new possibilities such as creating long straights. This can both decrease travel times, increase safety and lower the construction and design costs.

As AVs are introduced and become functional, OEMs are going to shift their focus from only removing the risk-taker (human driver) to improving other parameters of the vehicles, making them better suited to deal with problems compared to today's conventional vehicles. The ever-improving computing power, better and better sensors, and more efficiency within the vehicle's system will make vehicles improve over time. The competition between the companies will also help this development, the improvement of vehicles is necessary to stay on top of the competition as they fight for customers. Another important factor is the machine learning currently used by several companies (e.g. Google's Waymo). As the vehicles drive, they learn how other objects behave and tend to move. By always improving, AVs capabilities will never reach their full potential and they will be indefinitely improved. This makes these vehicles infinitively better than human drivers, which might already have reached their highest level as drivers.

Existing research has suggested that reaction time will improve as AVs develop further. Fagnant and Kockelman (2015), Lin et al. (2016), Farah et al. (2018), and Washburn and Washburn (2018) all stated that the reaction time will be improved over time, even though no quantitative estimate of the reaction time value is given. As the analysis showed, this parameter is important for the stopping sight distances, and thus vertical curvature but it also increase the chance of getting away from serious accidents due to unforeseen obstacles. The quicker the vehicle reacts to a hinderance on the road, the better. While within this analysis, reaction time was assumed 0,5 seconds, the reaction time used in design must be regulated and specified for all AVs allowed on the road. This is true for all other changes made to the road design or road elements, one must be sure that all allowed vehicles meet the necessary requirements before the road can be used.

As both literature review and interview showed, trucks, and AVs in general, will not see any massive changes to their performance characteristics in the early stages of implementation. Going forward towards 2050, the possibilities the technology possesses makes many improvements possible. However, with high certainty, the risk associated with errors made by human drivers will be removed with the first generation. With later generations and less certainty, it is believed that other parameters will be improved as well. These are often driver performance related, as this is one of the weakest points of today's vehicles. As improvements related to fuel efficiency and better driving behavior are not that important for road design, this research choose reaction time to be the most likely parameter with a possibility to have an impact on the design and physical infrastructure. As time goes and the technology improves, new features and ideas will certainly get more traction, but with the available data that exist today, there are no way to predict these changes. Therefore, it is concluded with that by 2050, risk and reaction times are improved, both of which can have impacts on the road design.

6.1.2 What elements of road design are impacted by autonomous trucks and/or truck platoons and how can they be improved?

Based on the prior analysis of changes in characteristics for future ATs, together with other literature, documents, and interviews, some elements and designs are likely to be impacted. As AVs and ATs will perform better in 2050 than conventional vehicles, the requirements in terms of minimum radiuses and so on could be lowered. This mean that many existing roads will not need any geometric upgrades, as they will already be accepted as good enough related to that new standard. The requirements listed in the analysis, will therefore mostly be regarded as a standard for new roads only meant for AVs. With a possibility and goal to enhance these vehicles' benefits and reduce construction costs.

However, when it comes to TPs, this may not be the case. Due to their much longer lengths and heavier loads than any other design vehicle ever used, they can impact existing roads in a totally different way. The analysis pointed out that ATs will be able to function on existing roads, with only minimal adjustments on certain elements (e.g. adding connectivity infrastructure in tunnels and at junctions). TPs, however, will possibly need more upgrades, especially when it comes to structures such as bridges and culverts, as well as pavement structures (although this is not analyzed here, but has been discussed in (Huggins et al., 2017, Fagnant and Kockelman, 2015, Turnbull, 2015)).

When designing a road, setting the alignment is a starting point. For the alignment, both ATs and TPs will function largely the same. As discovered in the analysis, the basic parameters of reaction time and speed were both likely to be impacted by AVs in 2050. Speed influences nearly all design parameters, but its impact was not as great as first thought with regards to the various parameters. This is especially shown in the stopping sight distance table 8, where the reduced reaction time had a much bigger impact on the stopping sight distance and then vertical curvature. When both reaction time and speed were adjusted, stopping sight distance requirements were reduced with an average of 31 % and vertical crest curves with 51 %. Vertical sag curves are only influenced by speed, and this therefore only saw a reduction between 0 and 5 %, highlighting what a big influence the reaction time has.

As mentioned above, the reduction of these basic parameters leads to a reduction in the alignment requirements. Conventional vehicles would not be able to travel at these roads, as they have higher reaction times. This also mean that existing road alignments should not present any problems for ATs and TPs, specifically related to the geometry. The changes that are made possible due to the improved AVs, allow roads to be constructed with sharper vertical radiuses, making it possible to better follow the terrain, saving money. The horizontal curves can also be decreased, but to a lesser degree than vertical alignment, and there are uncertainties in how much this would save or benefit the AVs. However, the biggest change and benefit is the flexibility that AVs give. A road's design is no longer determined by rules and guidelines created to keep drivers alert, awake and driving at the correct speed. Instead the alignment can feature long straights, wide curves without speed add-ons, sharper curves than before and neighbor curves do not have to follow the rules previously stated in earlier standards. This flexibility could be able to make roads more economical and environmental friendly, and other factors than humans can be used to decide a roads' design.

The width of a road is something that is often mentioned to be decreased due to AVs (Hayeri et al., 2015). The analysis concluded with a minimum requirement of 3-meter-wide lanes, as this would allow trucks, who can have a maximum width of 2,6 meters, to operate normally on these roads. This has nearly no impact on a 2-lane road as it currently stands with 3 or 3,25 meters wide lanes. But for a 4-lane road or higher, there are possibilities to increase the number of lanes and capacity in the same existing cross section. This is something that can be very interesting to utilize if the road has reached its capacity or if there are certain vehicles types that could need a designated lane. The increase in safety and accurate positioning due to GNSS and sensors will keep the vehicle inside its lane, creating a possibility to decrease or remove median barriers and its surrounding shoulders. It is very important to remember that outer shoulders should remain a certain width, due to the importance of emergency vehicles being able to pass and keeping a certain bearing capacity. This can give more variety of different widths and cross sections compared to what exists today. For new roads, it can decrease construction costs as less area is needed, but it is important to know if narrower lanes will increase the wear on pavements structures. This will require further investigations, and especially for TPs as their heavier weights can cause problems, further increased by the point of contact that will take place at the same place each time. This has yet to be fully understood, and different reports are concluding with different results depending on speed, traffic conditions, use and width of lanes (Lutin et al., 2013, Chen et al., 2016, Carsten and Kulmala, 2015). Another unknown is TPs' impacts on bridges. It seems that shorter bridges, with shorter spans, are more likely to be able to support a TP, as the forces are divided over several spans and pillars. It is when the span increase in length and more of the TP's load must be taken by each pillar, that problems can occur. This is maybe one of the most restricting elements of TPs as it is one of the most expensive to fix, but before a road is cleared for TPs, all bridges must be able to handle the higher forces. This is of course very dependent on the number of trucks in each platoon and their load.

Another element that is impacted by TPs are overtaking lanes. Due to their much longer lengths, minimum lengths for overtaking lanes might not be sufficient. From the analysis, overtaking distances were calculated for different platoons, all of which consisted of modular vehicle combinations, like in a worst-case scenario. Each time another truck connected to the platoon, the overtaking distance grew with 170 meters. While the overtaking distance for a standard 22-meter single truck were just around 100 meters, it had increased to around 600-800 meters for a five-truck platoon. This shows that the existing minimum requirement for an overtaking lane at 800 meters is too short. Now, it is not likely that there will be a five-truck platoon with a length of 153 meters on Norwegian mountain roads. A good assumption is to start with two trucks, as this will allow the public to get used to the idea, according to Janssen et al. (2015). However, current real-life tests have been using three trucks, without any big problems. These tests usually take place on highways and not mountain roads. However, as this research is being finished, a TP with three semitrailers just drove on the E8 in Troms. This only utilized the acceleration and breaking capabilities of the system and used a 2 second gap, but it shows that three-truck platoons are possible on mountain roads (Tu.no, 2018). A TP with three trucks would in the worst-case scenario of modular vehicle combinations be around 90 meters long and should likely be set as a limit as it combines benefits of several trucks in a platoon with a not too long overtaking or blocking distance.

It is possible to say that all AVs impact overtaking lanes. Because they do not break any speed limits, and if the speed limit is set to 80 km/h, as talked about in the speed analysis, all vehicles, trucks included, will be able to keep the same speed. There are hard to see why overtaking lanes on flat ground should still be created, although some instances could require it, for example when a tractor has to use the road. Overtaking lanes on flat ground could see a reduction because of this, but at the same time they are likely to see an increase in length, similar as in slopes. It is due to trucks' reduced speed in these steeper gradients that make overtaking lanes important today, and likely to keep them important in the future as well. To build extra lanes for over 1 km on a slope is not cheap, and it is not automatically cost-effective to construct this extra overtaking lane as AVs will not do any risky overtaking maneuvers. But this is something that would have to be considered for each unique project. With the length of TPs, it was showed that a two-truck platoon would in a worst-case scenario require 160 % longer overtaking distances compared to what most overtaking lanes are designed for today. The minimum length requirement should therefore become longer, and that length is dependent on how long platoons are allowed in Norway.

While the elements and design discussed above have been focused on changing the physical infrastructure, there are elements that are impacted in a digital way. Tunnels and junctions are two elements that can be largely impacted by connectivity technology. It is important to acknowledge the security risks of such system, and all processes that require connectivity or any other digital system, must be reliable in terms of functionality and overall uptime. If a system goes down or is hacked, the traffic could become congested or major incidents occur. Before implementing these system, either it is for junctions or other elements, they must be failsafe with a goal of no possibility of any failure. This might not be feasible, as new malware will always be developed to hack system such as these. But as Fagnant and Kockelman (2015) mention, huge national and international installations like power grids and air traffic controls have managed to stay ahead of hackers and software failures, and the same type of safety must be implemented with the systems of an AV or the infrastructure around.

As the interview and some existing research revealed, road design and infrastructure does not seem to be the biggest issues for implementation, but rather the lack of digital infrastructure, accurate positioning and digital maps. This could lead to several changes in the physical infrastructure, as discussed earlier, like narrower lanes, reduced chances of accidents, and higher efficiency. But in tunnels, and some other areas, satellites signals cannot reach the vehicles or read their position. Some literature mentioned this as a problem, and the interviewee stated that V2I technology could solve it. Further research revealed that these technologies are under development. While there are many tunnels in Norway, and many of them are small, dark and of low quality, the connectivity technology seems to be able to address some of those problems and not just the positioning. For example, if a tunnel is too narrow or too low, forcing trucks to drive in the middle, V2V or V2I can ensure that all other vehicles wait at the end of the tunnel until the truck has passed. This is the case of several tunnels on small coastline roads, and this would be a more effective solution than traffic lights as there would be no delay in the system. The system will know as soon as the truck has passed, letting other vehicles drive. This technology can also help warn about rock falls, closures or fogging windows to mention some.

An area where connectivity has already been simulated, is junctions. The analysis explained that junctions cause issues for AVs as merging and the high number of objects makes it difficult for the systems to estimate everyone’s directions. For interchanges or ramps, merging and out-of-sight vehicles cause problems. With high speeds and objects blocking the local perception of sensors, it can be difficult for the AVs to merge onto the main road. It is said that connectivity can solve this, as it will allow vehicles on the main road to choose another path, slow down or accelerate past, whatever is the most efficient at the given time. This is an even bigger problem for TPs, as they change lanes simultaneously and their long length require a lot of free space. To ensure TPs can manage these situations without de-coupling, communication between vehicles seems necessary. For intersections, the addition of connectivity has given amazing results during data simulations. Systems where all lanes are allowed to drive at the same time have been tested, with each vehicle given a certain path, the throughput have been increased by a massive amount. With these systems, roundabouts will no longer be efficient, and should be replaced by X and T-junctions as these allow vehicles to keep a higher speed and more direct routes, decided by a connectivity system.

It is also easier to install connective technology in specific areas, like tunnels or junctions, instead of whole roads. But both junctions and tunnels need more extensive testing, especially with trucks and TPs, as these require more space than an ordinary car. Tunnels require all vehicles to be connected, because a "signalized" tunnel, as the examples above, cannot function if one vehicle does not stop as intended due to not receiving any messages. The slot-based intersection requires all vehicles to be connected and automated, as a driver in that mix would create chaos and the system would lose its efficiency benefit. The system is based on very thin margins, something a human would not cope with.

This analysis left some parts of impacted elements out of the analysis, due to them already being solved, understood or not yet researched. Mentioned mainly by the interviewee and Huggins et al. (2017), this elements are pavements structures, signs and lane markings. Point of contact due to precision driving and the load dynamics and weight of TPs are likely to have impact on the pavement, but this element is still not fully researched. Signs are known to create problems due to their fonts, wording, placement and so on, this was reported by automakers in Huggins et al. (2017)'s report. They also mentioned issues with lane markings, and that cuts in the surface can sometimes be thought to be markings. Solutions for both sings and lane markings are to create more international standards, making it easier for AVs to be programed to understand. Connectivity technology can also help in this area, and it can make signs excessive, if there are no human drivers left to read them.

6.2 Challenges with study

This research has encountered many challenges and limitations, and most have to do with the topic of AVs in general being so young, with platooning even younger and more specialized.

The first section will discuss the weaknesses and limitations of the different methods, with the following sections discussing the analysis, results and case study.

6.2.1 Method

During the literature review it became obvious that the due to AV technology's rapid development, published literature was not always up to date, with many articles showcasing older and less advanced technologies. This makes it hard to know what the future will bring, and what "knowns" to base this research on. To mitigate this issue to a degree, different tech and well-established sites on the Internet (e.g. tu.no and self-driving-future.com) had to be used to get the current research results which had yet to be published in the more reliable article or report form. This may influence results and make them less reliable, but it seemed a necessary action to keep the relevance of this research up to date. To counteract for the less reliable data, it was attempted to find several sources, although this was not always a success.

Another problem due to a very young field of study, was the lack of precise literature. At this early stage of AVs and TPs and without many real-life tests or any implementation, there are not much data or experience to base this research on. Companies are still very secretive with releasing information that could give them an advantage over their competition, which also seemed to be the case with the conducted interview. This was reflected upon in the method chapter. A result of this, all literature takes use the same results. Literature on TPs all use the same 5-6 big tests with the same empirical results regarding fuel efficiency improvements. Some add discussions about legal and policy issues, and some have discussions and own throughs. (e.g. Janssen et al. (2015) or Farah et al. (2018)). Research conducted on future road infrastructure, mostly use discussions and own knowledge together with a few real-life experiences from lower levels of automation, and some interviews with manufacturers and road operators (e.g. Huggins et al. (2017) and Farah et al. (2018)). Most of this literature does not have much empirical evidence to show for, most of it is therefore based on knowledge and statements from experts, manufacturers, authorities.

Issues regarding the document analysis consists of the use of Norwegian documents. Both road design handbooks and technical drawings are for the Norwegian context and that makes this research focused on these specific conditions. Theoretical concepts within road design are universal, but there are differences within application that are country or area specific. These results should be transferable, but one should be careful to accept the conclusion without checking formulas or assumptions for own areas.

The technical drawings showcase a very modern 2-lane road with a higher capacity of vehicles. It is used as a “common Norwegian road” and its elements are used for further analysis. Most of the roads in Norway will not be of the same standard and are likely to have different features and elements. To ensure a representative selection of the Norwegian road network, more and different types of roads should have to be included in the analysis. Due to time restrictions, this was not done and will likely affect the results.

6.2.2 Analysis and Results

The analysis was challenging due to the lack of data and general knowledge mentioned above. While there is knowledge on AVs, ATs and TPs, it is nearly impossible to predict a future for these vehicles by 2050. This was even mentioned by the interviewee, who said that due to the rapid development, new ideas and features can develop at any given time, making it impossible to predict what technologies will be used in 20 years. New ideas, such as subscriptions to vehicle fleets and no longer having private cars can shake up the transport system as we know it. This is likely to increase the need for transport, both of people and goods. As the world’s population grow, and more people can afford to buy food and other goods as well as luxuries such as travel, the demand will increase further.

This analysis tries to focus on trucks, and to allow for this rise in transportation needs, ATs and TPs can contribute with using less energy and releasing less pollution. There is also a bigger and bigger shortage of truck drivers all over the world, something that can increase the development of driverless trucks and TPs (Costello and Suarez, 2015). Authorities see the benefits of AVs and TPs, especially when it comes to fuel consumption, emissions, safety and congestions, but also industry and jobs, and they are pushing companies and researchers to get the technology to an operative level (Bonneau and Yi, 2017). Before that, policies and laws in most countries must be changed to allow the vehicles access to public roads. This process is often slow and filled with political arguments. All these factors make it hard to predict a timeline for when the technology is implementation ready.

The analysis built on assumptions of no mixed traffic and that all vehicles are connected. If all vehicles are autonomous, it is fair to assume they are also connected. Even though they are independent of each other, they greatly benefit from working together and whenever someone talks about AVs, it is normal to think that the vehicles are also connected. However, assuming no mixed traffic is a bold statement and it can only be achieved if either policies and laws forbid conventional vehicles or certain roads only allow AVs. It is very unlikely that within 30 years all vehicles are changed to autonomous without some policies or incentives helping people to change. As Sparrow and Howard (2017) stated in their report, it is not morally correct to allow vehicles driven by humans to exist when there are far better options that could help save lives. They said that a human driving together with AVs, is the equivalent of a drunk robot trying to keep up with the superior speed and efficiency of AVs. So, without any policy changes, one cannot assume that all vehicles will be autonomous, making the results of this thesis a best-case scenario.

This thesis is an exploratory study and it is therefore focused wider rather than deeper. This choice was done on the background of the scarce literature and existing data found during the pre-study. Its results are then best served as a tool to point in what direction further research should move towards. While this research does present tables of minimum requirements for road design parameters, these are based on a very little existing database and own thoughts and knowledge gained through this study. A big challenge and disadvantage with this is that everything is done by one person and all thoughts are colored and based on prior research, as well as how that person view the future. This type of study might be better utilized when there is a bigger group of people all contributing with different opinions, knowledge and thoughts.

6.2.3 Case study

While the NPRA's databank (NRDB) provides lots of data, it can be difficult to use for this specific purpose. It is divided into small sections, not comparable to any technical drawing, as explained in the method. Radiuses can be very different, even if they are taken from the same corner which should have a constant radius.

The road should lead the driver with both vertical and horizontal curvature, but as the road is divided into so many small fragments with no specific length, these parameters are near impossible to combine. The results from the case study have therefore not taken this part of road design into consideration. Although there are solutions (e.g. ArcGis), this case study is rather a mean to get a more viewable presentation of the data. This simplified procedure was viewed as good enough, with each design parameter presented by itself.

Of other road design parameters that could be of importance for trucks, slopes would have been an important parameter to look at. However, when retrieving this parameter from the databank, it was in such a fragmented state that the different grades would be near impossible to use in any sort of analysis. Due to that state of the data, it was viewed as too time-consuming to use. Instead, road width was chosen, as this can be a common problem with older Norwegian roads.

By comparing and discussing the results against existing literature, the subjectiveness of the case study should be upheld. The researcher's own thoughts and views, together with the many assumptions regarding the future trucks characteristics, can make the results from the study biased. However, by strictly following the results from the earlier analysis, biased views during the discussion are reduced.

6.3 Future research

Many of the same reasons as to why this study was a challenge, are also the reasons used when explaining further necessary research. It is impossible to foresee a future with the technology and rapid development that exists today. The technology has to mature a bit before a future can be predicted with a good enough certainty to create road design standards. Data needed to calculate requirements in these standards must also be real-life tested and preferably used for some time on a bigger scale, compared to what is seen today.

Future research should concentrate on all parameters and elements analyzed and discussed above, with more additions, as it is likely that other areas of interest will show itself when more knowledge and experience are gained. That research should focus more on mixed conditions, as that the first big problem presented. It should also focus on maintenance and wear of the infrastructure, which has not been discussed during this thesis.

Digital infrastructure must be investigated, especially for junctions that are currently huge bottlenecks in urban areas. This must also be tested with the use of TPs. Tunnels is another area where the use of connectivity should be developed further, and as this is a major problem surrounding the Norwegian coastline and the transportation of Norway's second biggest export, fresh fish, this is of great value.

The main issue at this given time, is the characteristic development of AVs versus conventional vehicles are so difficult to understand. With every iteration of a new generation of AVs, there is a possibility of an improved vehicle. It will likely be more in the line of how computers and other technological instruments develop today, than how conventional vehicles have developed. This development can cause issues when creating new road standards, as the basis used for those standards will be older and outdated much quicker than today. With construction projects often being slow and expensive, this development is difficult for physical infrastructure to keep up with. It is more likely that the development of AVs will be based on whatever road standards that is used at that time, like the development of AVs today. This will allow roads to be more future-proof and not require as many upgrades as the vehicles are likely to receive, making future prediction and research a bit easier.

7 Conclusion

The objective of this research was to see how ATs and TPs could impact road design and physical infrastructure by 2050. This was done by collecting knowledge and data from literature, documents and interviews, and examining these new types of vehicles' driving behavior and performance characteristics. The conclusion of this exploratory study was reached by a discussion with a basis from the three research questions:

1. What is the differences in vehicle characteristics for conventional trucks vs autonomous trucks?
2. What elements of road design are impacted by autonomous trucks and/or truck platoons?
3. How can these elements be improved to be supportive of autonomous trucks and truck platoons?

The conclusion of this thesis is that in general there is still too little data available to be able to fully predict what an autonomous future will mean for road design in 2050. But, with today's existing technology, road design can and is likely to change. Through the analysis and discussion, those changes were found not to be the specific parameter which this thesis set out to find, but rather the flexibility AVs open up for. Road design will not need to be based on the guidelines set to keep human drivers alert, but can instead focus on other factors such as travel time, environment and economical effects, as well as enhancement of AVs' and new drivetrain benefits. Due to, for example, faster reaction times, some alignment parameters can be reduced, but this is not a large change, it just adds to the flexibility. For some elements, digital infrastructure is likely to create large changes, for example for junctions and its bottlenecks. Additionally, TPs will likely impact structural elements such as bridges and pavements.

It is important to remember that mixed traffic conditions will be the norm for many years. While mixed traffic conditions were not the initial assumption in the thesis, it was discovered that this is likely the biggest challenge. Manufacturers are developing autonomous technology based on existing road design given the mixed conditions. Later generations of AVs should also be based of the existing road design and not the opposite. As discussed, these vehicles are now more like phones in their development, with each new generation adding new improvements and features, making it impossible for the roads to keep up.

This study has been an exploratory study based on limited literature and data collections related to the physical infrastructure. This study looks at geometric design as a whole, but for more precise results and handbook-ready publications, research on each basic and design parameter and infrastructure elements should be conducted. Especially in regard to TPs, which will add new load dynamics and higher weights on bridges and other structures. Before that research can take place, more reliable quantitative data must be gathered about AVs and their requirements. International standards for AVs should also be introduced before requirements for future road design are defined.

The technology of vehicle automation is still young, real-life tests are still few, far apart and with low penetrations of AVs, thus research within this field is only expected to grow.

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Part 2: Scientific Paper

PHYSICAL INFRASTRUCTURE NEEDS FOR AUTONOMOUS & CONNECTED TRUCKS: AN EXPLORATORY STUDY

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1 INTRODUCTION

With automotive transport in large proportions contributing to several key issues including fatalities, energy consumption, greenhouse gas emissions and traffic congestion, current advances in vehicle technologies allow for potential future improvements. With research and testing of connected and automated vehicles (AV), public discussions, successful demonstrations of these technologies, and promises of considerable benefits have ensured a high anticipation of these vehicle innovations.

Heavy vehicles have a significant role in contributing to these key issues. In Norway heavy-duty transport stands for one tenths of all CO_2 released, and road transport is expected to double by 2050 (Ssb.no, 2017, Hovi et al., 2017). At the same time, a truck driver shortage is starting to emerge, creating issues due to higher transport prices (Long, 2018).

Autonomous and connected trucks (AT), and in extension, truck platoons (TP), are viewed as legitimate solutions due to their expected benefits. But concerns have been raised by several parties, including vehicle manufacturers, on how certain road infrastructure elements will be impacted by and limit the use and benefits of AVs, ATs and TPs.

This paper takes aim to answer the following research questions to assess how ATs and TPs can impact the road infrastructure in 2050:

1. What is the differences in vehicle characteristics for conventional trucks vs autonomous trucks?
2. What elements of road design are impacted by autonomous trucks and/or truck platoons?
3. How can these elements be improved to be supportive of autonomous trucks and truck platoons?

This research concentrates in categories of geometric alignment (e.g. curvature), specific road specifications (e.g. widths), and specific road elements (e.g. tunnels, on/off ramps). As the paper assesses the future, it is assumed that all vehicles have reached SAE's automation level 5 and that all vehicles are connected. It is also assumed that there is no mixed traffic, either by 100 % penetration of AVs or by looking at AV only roads.

2 THEORY

Most of the existing literature surrounding AVs have to do with their expected benefits, such as safety and fuel consumption improvements (Litman, 2013, Lin et al., 2016, Fagnant and Kockelman, 2015). Some examine the effects of and expected timelines of truck platoons (Janssen et al., 2015, Poorsartep and Stephens, 2015, Tsugawa et al., 2016). Truck platoons are found to help decrease energy consumption, congestion, emissions and help with the rise of transportation as a shortage of drivers start to show (Costello and Suarez, 2015). Digital infrastructure is also an area who receive much attention, with the addition of communication between vehicles and infrastructure, highly detailed maps, positioning technology and so on (Pype et al., 2017, Sanchez et al., 2016, Hayeri et al., 2015, Farah et al., 2018).

2.1 Physical Infrastructure

There is scarce literature on the physical infrastructure and how new types of automated driving vehicles might influence change, either to enhance their benefits or necessary to make the road supportive. Huggins et al. (2017) has conducted research on this field, both with regular AVs (cars and trucks) and truck platoons. The report found one of the biggest issues to be a lack of international standards for the roads and surrounding environment, including signs and markings. Vehicle manufacturers stated that this caused issues, everything from placements to spacing and different wording decreased the vehicle’s sensors and brain to successfully read and understand the environment.

Another big issue was found to be truck platoons. The physical infrastructure is not designed or constructed to support such long and heavy units. The length can create issues with junctions, on/off ramps and overtaking. The increased load and possible different load dynamics can create issues for bridges and other structural elements, as well as heavier and faster wear of pavements. Other researchers have found this to be dependent on different factors, including speed, traffic conditions and type of use (Lutin et al., 2013, Chen et al., 2016). This would also be affected by the width of lanes, which are suggested by Hayeri et al. (2015) and others to become narrower. Better positioning technology, as sensors and GNSS, will allow vehicles to travel more accurately within their own lane, making it possible to reduce the width of each individual lane.

Huggins et al. (2017) concludes that with AVs having differing characteristics compared to today’s conventional vehicles, geometric design, widths, and different road elements are set for possible changes. Washburn and Washburn (2018) also concludes that as geometric alignment is dependent on vehicle performance and sight distance, possibilities for changes are present as AVs at introduced. They and Fagnant and Kockelman (2015), Lin et al. (2016), and Farah et al. (2018) also stated that reaction time would decrease over time, lowering the necessary stopping sight distance.

2.2 Digital Infrastructure

The digital infrastructure has a huge part in automated driving technology, although vehicles can operate without connecting to the infrastructure. Digital infrastructure includes highly accurate digital maps and vehicle positioning, road databases, sensors, connectivity and cloud-systems (Farah et al., 2018). It addresses many of the issues with transportation, especially since it allows vehicles to communicate either with each other (V2V) or to the infrastructure (V2I). Information and communication technology (ICT) is one of the most important technologies as it allows the system to gather, store, manage, and exchange data. It is also a necessity to get truck platoons to function.

2.3 Norwegian Road Design

Road design in Norway is based on vehicle characteristics and assumptions from the 1950s and 1960s. Recent efforts aim to update the design standards, including considering the impact of AVs. The requirements and standards are presented in several topic-specific handbooks published by the Norwegian Public Road Administration (NPRA).

The most important handbooks for road design are N100 and V120. The N100 handbook states the requirements and guidelines for building new and upgrading existing roads and streets, as well as some overlying information regarding different road elements. Handbook V120 addresses the theoretical concepts used to calculate the requirements and guidelines of N100.

The road alignment is built up by basic parameters, which are specific to vehicles, humans, surroundings and statistics. These parameters are used when calculating the requirements. Figure 1 show the correlation between these basic parameters, minimum requirements and design parameters.

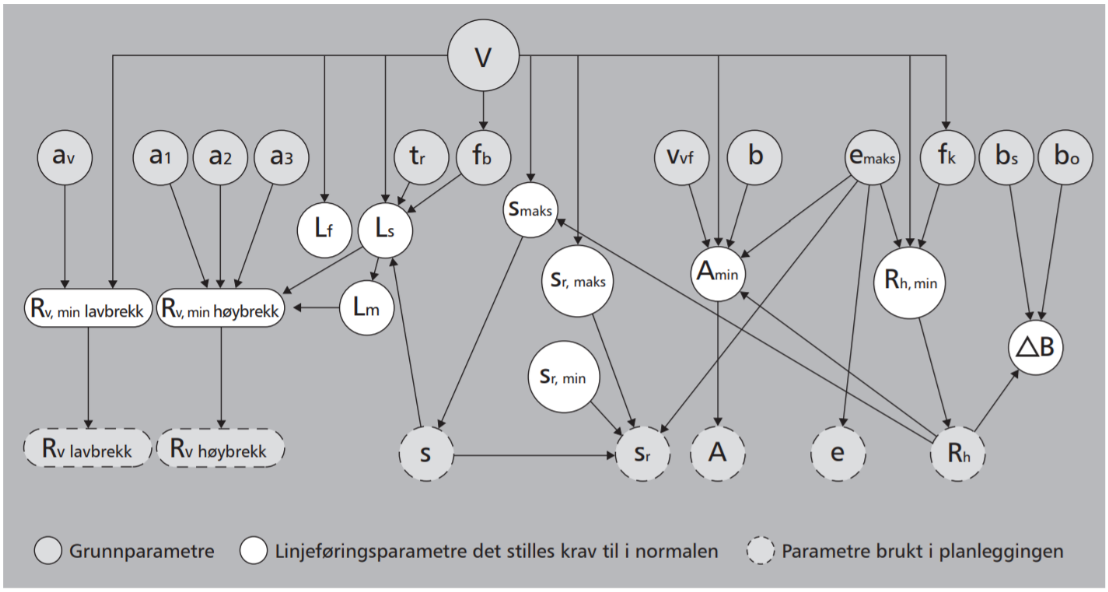

Figure 1. Correlation between road parameters (NPRA, 2014)

3 METHOD

To explore possible impacts by ATs and TPs on road infrastructure and how the design can best enhance their benefits, the research built on the characteristic differences between conventional trucks and ATs. Based on a pre-study, which found limited knowledge and a scarce quantitative data, an exploratory approach towards the task was chosen. This included using the qualitative methods of literature review, document analysis and interviews.

The research design used all three methods to gather data and knowledge, to which the analysis and discussions were based on. The methods are described in the following paragraphs.

3.1 Literature Review

To map existing research and gather knowledge, a literature review was conducted. As first revealed in a similar method during a pre-study, literature on future road infrastructure is scarce and search words have to be specific. “Truck platoon”, “autonomous vehicle”, “autonomous truck”, “road infrastructure”, “future road design”, and “physical infrastructure” were some of the used key words. This method gathered most of the existing literature with corresponding research and knowledge.

3.2 Document Analysis

The Norwegian road design handbooks, created by the NPRA, were studied and used during the analysis of each design parameter. These books gave the knowledge and understanding on how roads are designed in Norway. Several handbooks were used, but most notably N100 (*Road and Street Design*) and V120 (*Premises for Geometrical Design of Roads*).

3.3 Interview

Due to the scarce literature and a very young field, it was hoped that interviews with truck manufacturers with autonomous research departments would provide new and exciting information surrounding the differences in vehicle characteristics and needs for both ATs and TPs. But as the technology is rapidly developing and highly competitive, it was challenging to gather specific information from manufacturers. One OEM provided interview information used within this study.

4 RESULTS

4.1 What is the differences in vehicle characteristics for conventional trucks vs autonomous trucks?

Initially, performance characteristics are not expected to change much for ATs, other than normal improvements and new drivetrains (e.g. electric trucks). The interview revealed that automated driving could unlock new possibilities but at this given time, it is not something that can be predicted. Existing literature did neither mention any major changes in this regard. The literature and existing research showed that as the human driver is replaced, the driver related parameters are what will change. Only one of these parameters are directly influencing road design, that is reaction time (also called response time). This parameter is the time it takes to react to something and then start a movement and is in Norwegian road design sat to a constant of 2 seconds. For the first generation of AVs and ATs, this parameter will not improve over humans, according to the interviewee. OEMs will only concentrate on removing the driver, all other parameters will not be improved compared to a conventional vehicle. The reaction time used in design (2 seconds), is not a true reaction time but instead covers all conditions and individual characteristics of humans. When driving, the reaction time has been found as on average 0,63 seconds with a standard deviation of 0,07 seconds (Nagler and Nagler, 1973). The reaction time of first-generation ATs could therefore be expected to be an approximation around this number. Over time, the sensors and computing power will become more efficient and lower the reaction time of the vehicle further. Later generations of ATs will therefore be able to keep a much lower reaction time than the 2 seconds used to calculate certain design parameters today.

The second difference ATs bring, is the removal of risk. This is not a basic parameter and will not directly influence road design parameters, but it will greatly change the way vehicles behave and their safety. The interviewee stated that the removal of humans, and thereby risk, is the most important factor for the first-generation of AVs. Several big OEMs have stated that humans are slow responders, easily distracted, and inattentive (Cleantechnica.com, 2017, Autox2xtech.com, 2017). By replacing them, vehicles will not take unnecessary overtakes, be inattentive, speed, drive drunk and more, creating a possibility to change or remove safety factors used in road design, as well as creating new and less stimulating road designs. This risk reduction aspect will be introduced with the first-generation of AVs and improved with later generations.

TPs introduce new and much longer lengths than what has ever been seen on most normal roads, and with it comes different load dynamics and higher weights. From the current 2018 Norwegian road design handbook N100, modular vehicle combinations with a maximum length of 25,25 meters have become the design vehicle for most larger roads. A TP with just two semitrailers are likely to double this length (Janssen et al., 2015), creating issues with roads that were never designed for such unities of vehicles with that kind of length. Together with the much heavier load on a shorter distance than what is currently normal, these are the biggest impacts on the road infrastructure.

4.2 What elements of road design are impacted by autonomous trucks and/or truck platoons? And how can these be improved?

The geometric alignment is influenced by the reaction time directly, and by the removal of risk indirectly. By removing the risk-taking driver, speed add-ons can be removed or minimized. As the design speed is higher than the actual speed limit, due to these speed add-ons, the design speed will become closer to the actual speed limit. When calculating the different design parameters, design speed is used, and as can be seen in figure 1, it influences most design parameters.

If the reaction time of first-generation ATs are assumed to have the same value as humans, 0,63 seconds (Nagler and Nagler, 1973), it is fair to assume that by later generations, it should have been reduced below 0,5 seconds. Creating a minimum geometric requirement based on this value means that all vehicles driving at that time must have the same or lower reaction time, thus all be automated. This would reduce the reaction time used for calculations by a 75

%, greatly lowering minimum requirements of both stopping sight distance and vertical crest curves, as can be seen from the correlation figure (1).

Speed add-ons added to the speed limit can be divided into two within Norwegian design. One for safety measures to take into account unpredictable conditions (for example, friction), and one for the risk humans tend to take, especially at larger curves where higher speeds are often observed. AVs will not break the speed limit and it is therefore possible to remove the risk add-on. As unforeseen events can still take place, like black ice or an animal jumping out in the road, the safety add-ons should only be reduced, which is a possibility due to the faster reaction time. For this analysis, the safety add-ons were reduced by 30 %.

Using road types and formulas discovered during the document analysis of Norwegian road design handbooks, average changes to minimum requirements of the most notable geometric parameters were calculated. Compared to current minimum requirements, stopping sight distance would see an average 75 % reduction to its distance, which would lead to vertical crest curves seeing an average of 51 % reduction in minimum radius. Horizontal and vertical sag curves only saw smaller improvements (below 9 %) on a few road types. Reason being that these are only affected by the change of design speed and not the larger change of reaction time.

Based on the differences in driving behavior, specifications and new features (e.g. connectivity and accurate positioning), specific road elements are also likely to be impacted of the introduction of ATs and TPs. These include lane width, tunnels, bridges and junctions.

For lane width, it is possible, due to more accurate driving and positioning technologies, to create narrower lanes and make room for additional lanes in the same cross section or reducing the necessary area used when constructing. Assuming a lane width of only 3 meters, as used on the narrowest 2-lane road with an 80 km/h speed limit, a standard Norwegian 4-lane road could fit a 5th lane. The reduced risk gained from accurate driving could also indicate that median barriers and the inner shoulders could be removed and/or reduced. This open up many possibilities of new and narrower cross sections or with more lanes in the same space. For 2-lane roads, the standard lane widths and cross sections are not enough to fit a 3rd lane, but it is achievable here to reduce the cross section.

Bridges are an element that is likely to be impacted by TPs, as mentioned by Huggins et al. (2017). This is not an extensively research subject, but due to the trucks close proximity, their combined weight will add more stress on longer spans than current conditions. While the load dynamics of TPs are likely to be different, possibly creating challenges for the structural integrity of pavements, it is the combined weight which could be an issue for bridges. As this is yet unknown, most real-life tests of TPs are obliged to de-couple when traversing bridges (Tom Alkim et al., 2016). While more research is needed, it is possible that bridges must be strengthened to be able to support TPs, especially bridges with longer spans where pillars or other elements will have to take more forces than before.

Another problem that exists on bridges, but also along some stretches of road, are railings. While AVs in general are seen as safer options when fully functional, accidents will occur. There are possibilities that TPs will drive off the road and current railings are unlikely to be able to withstand the forces created by 2 or more trucks crashing into it at the same time (Janssen et al., 2015). New and stronger railings must be designed and fitted to stretches with the most risk and highest consequences.

TPs length is also problematic for current overtaking lengths. Minimum lengths are currently 800 meters with 100 meters on each side for widening of the road. Due to trucks maximum speed of 80 km/h in most of Europe (Europa.eu, 2018) and that other AVs cannot break the speed limit, overtaking lanes might only be necessary during slopes where trucks lose speed. Following Janssen et al. (2015)'s gap of 0,3 seconds and speed of 80 km/h, calculations for necessary overtaking distances are shown in table 1 below, looking at different lengths of platoons. Overtaking lanes are only present where truck speed is 15 km/h slower than the average speed, as this is where the speed difference is a safety concern according to Glennon (1970). Overtaking distances is calculated with speed differences of 15 and 20 km/h accordingly, any bigger differences will only decrease the distance, and this should be a worst-case scenario. This is also why modular vehicle combinations are used, as these are the longest trucks allowed on Norwegian roads.

Table 15. Overtaking distances

Numbers of trucks	Total length (front to back)	Overtaking distance (15 km/h difference)	Overtaking distance (20 km/h difference)
1	25,25	134,67	101,00
2	57,17	304,89	228,67
3	89,08	475,11	356,33
4	121	645,33	484,00
5	152,92	815,56	611,67

The results clearly show that a current minimum length of 800 meters for overtaking lanes are too short when the number of trucks in a platoon increases.

Road elements like tunnels and junctions will change with the introduction of AVs and ATs, but not necessarily in a physical way. These elements are highly dependent on digital infrastructure to be able to support these new vehicles. Tunnels require V2I communication systems to be able to withhold the accurate driving level when GNSS is not available, according to the interviewee, Kim and Jung (2016) and Hoang et al. (2017). Junctions are very difficult for AVs in general, and even harder for TPs due to their length (Tom Alkim et al., 2016). These traffic systems are complex, but with the help of V2V or V2I, a system can coordinate all the vehicles to achieve a much higher throughput than what is possible today. This affects both merging at interchanges and ramps, and normal intersections (Maarseveen et al., 2017). Simulations where all vehicles are connected and automated have shown great results for intersections, making it possible to remove traffic lights and roundabouts (Ackerman, 2016, Huggins et al., 2017).

5 DISCUSSION

The automation part of ATs does not impact the alignment or any other road element any different than a normal autonomous car. ATs will be built to function on the current roads and will require only small changes to create a more seamless experience. As long as the vehicles remains roughly the same, in terms of dimensions, weight and performance, the same infrastructure will be able to handle them in the future as well. TPs, however, are a brand-new unit of vehicles, adding more weight and length, as well as complicating traffic conditions due to that length. To accommodate for this, structures must be able to withstand the increase in forces and certain other elements must be changed only because of the length.

As the results and existing literature show, the improved characteristics of ATs will lower the minimum requirements of many design parameters. With the information that exists today, vertical crest curves and stopping sight distances are the parameters who are significantly improved as reaction times has a much bigger impact than the speed. But as speed influences most design parameters, nearly all will be improved to some degree. The difference in improvement can be seen between stopping sight distance and horizontal curvature, when stopping sight distance is impacted by reaction time and design speed, and horizontal curvature, just design speed.

AVs in general, will have bigger impact on other factors, not related to any design parameter. This is the way roads are designed, with the rules of optical guidance and that horizontal and vertical curves work together to create a road that is easy to understand and easy to drive at the correct speed limit. With the introduction of AVs and their different driving behavior, these rules do not longer need to apply. The road no longer need to be esthetic pleasing for the driver to stay awake, there can be repetitive straights instead with sudden sharp corners. So instead of concentrating on the lower minimum requirements, these new ways to design roads are viewed as more important and opportunistic, as it can make it possible to create cheaper and faster (i.e. travel time) roads. The lower minimum requirements can be of use occasionally, for example can improved vertical curves help reducing lengths of tunnels and bridges, saving money. By creating straights instead of corners, the forces on pavements are reduced and the wear and maintenance should be lowered as well, which can possibly counteract the higher wear created by accurate driving and TPs.

The lane width is something many experts think will become narrower, with some mentions of lanes completely disappearing as V2V communication takes over. For this exploratory study, a lane width of 3 meters were chosen as this is the standard on the narrowest 2-lane road with 80 km/h. This ensures that trucks, with a maximum width of 2,6 meters, will fit within the lane. New constructions can possibly take up less space. Roads that have 4 lanes or more usually have wide lanes to keep a higher safety standard, and in Norway these roads use a minimum lane width of 3,5 meters. They also have large outer shoulders and median barriers. With the lanes reduced to 3 meters, another 1 meter can easily be taken from either of those areas to result in an additional lane. This research recommends taking 0,5 meters from each side of the inner shoulders or median barrier, as the other shoulder is used for emergency and maintenance vehicles and should remain untouched.

By introducing a new lane, this can be used for whatever purpose that is important on that unique road. It could become a TP lane or just a truck specific lane, if that road has a high percentage of trucks. If one way has more traffic problems than the other, the extra lane can be used to increase the roads capacity. It is also possible to completely remove the median barrier, due to the higher safety and accurate driving, and alternate which direction the extra lane is used for, changing the lane for each rush hour. This can be useful for roads leading into cities.

The accurate driving needed for these narrower lanes require highly accurate positioning systems, usually GNSS systems. Whenever this is not present, as in cities or tunnels where signals cannot reach or can get distorted, V2I communication can be used, as stated by the interviewee. To get narrower lanes, this is likely a necessity for tunnels and high-density areas. There has not been enough research conducted on this area, making it hard to conclude with anything other than that OEMs say this would be required.

Bridges seem to be the biggest issue for TPs, as their increased weight can become too much. The research on this issue is scarce and make it hard to conclusive state that bridges must be strengthened. To have TPs de-couple at each bridge is not beneficial and can cause other problems, such as other vehicles between the trucks and dangerous situations during reconnection. As Norway has a lot of bridges, a solution could be to only allow platooning on certain roads, for example the bigger main roads. To possibly fix all bridges is likely to be very expensive and it might not be cost-effective. This is something that must be decided on a national level.

Junctions, and especially intersections, have always been a bottleneck element. With the use of connectivity, it seems that this element can get much higher throughput, at least when looking at the results from simulations of slot-based junctions. This works best in X or T-junctions, roundabouts should therefore be converted. Pedestrians and cyclists would require their own infrastructure to keep the soft users away from the automated junction. Any crossing that would require the traffic to stop would interrupt the flow and the system would be no different than today's traffic light intersections. When it comes to interchanges, ramps present the biggest problem. AVs in general have difficulties with merging, and the local perception its sensors gives are sometimes of too short distance or restricted due to obstacles. Connectivity can produce a bigger range for the vehicles perception, as well as control the vehicles to make the merging as effective as possible. TPs changes lanes simultaneously and need more free space, something that such a system should be able to give it. It is also likely this would need longer ramps, depending on the allowed platooning length. These systems will require both connected and automated vehicles, as the system will take control over the vehicle by giving it a slot. It requires more precision than a human driver can provide, there is also no place for risk-taking, something humans tend to do.

The digital infrastructure is very important for the future of ATs and TPs, and it is important to acknowledge this when designing roads for the future. Both physical and digital must work together to best utilize the benefits these new vehicles can provide, and the best result will come when these are designed together. This field has been shown to be very young, with little to none research done on some elements. Signs, markings and pavement structures have not been mentioned, but these are well explained in Huggins et al. (2017)'s report.

6 CONCLUSION

The objective of this research was to see how ATs and TPs could impact road design and physical infrastructure by 2050. In general, there is still too little data available to be able to fully predict what an autonomous future will mean for road design in 2050. But, with today's existing technology, road design seems likely to change. Through the analysis and discussion, those changes were found not to be the specific parameter which this paper set out to find, but rather the flexibility AVs open up for. Road design will not need to be based on the guidelines set to keep human drivers alert, but can instead focus on other factors such as travel time, environment and economical effects, as well as enhancement of AVs' and new drivetrain benefits. Due to, for example, faster reaction times, some alignment parameters can be reduced, but this is not a large change, it just adds to the flexibility. For some elements, digital infrastructure is likely to create large changes, for example for junctions and its bottlenecks. Additionally, TPs will likely impact structural elements such as bridges and pavements.

It is important to remember that mixed traffic conditions will be the norm for many years. While mixed traffic conditions were not the initial assumption in the thesis, it was discovered that this is likely the biggest challenge. Manufacturers are developing autonomous technology based on existing road design given the mixed conditions. Later generations of AVs should also be based of the existing road design and not the opposite.

Before more research can be conducted, more reliable quantitative data must be gathered about AVs and their requirements. International standards for AVs should also be introduced before requirements for future road design are defined. The technology of vehicle automation is still young, real-life tests are still few, far apart and with low penetrations of AVs, thus research within this field is only expected to grow.

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Part 3: Appendix

Appendix 1	-	Agreement concerning MSc thesis and supervision
Appendix 2	-	Interview

NTNU

Agreement concerning MSc theses and supervision

This Agreement confirms that the topic for the MSc thesisis approved, the supervisory issues are agreed and the parties to this Agreement (student, supervisor and department) understand and accept the guidelines for MSc theses. This Agreement is also subject to Norwegian law, the examination regulations at NTNU, the supplementary provisions and the regulations for the MSc Engineering Education programme.

1. Personal information

Family name, first name: **Paulsen, Johan Tobias**	Date of birth **October 22, 1993**
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2. Department and programme of study

Faculty **Faculty of Engineering**
Department **Department of Civil and Environmental Engineering**
Programme of study **Civil and Environmental Engineering**

3. Duration of agreement

Starting date **January 15, 2018**	Submission deadline* **June 11, 2018**
If part-time study is approved, state percentage:	

** Including 1 week extra for Easter*
All supervision must be completed within the duration of the agreement.

4. Thesis working title

Challenging Road Infrastructure for Autonomous Truck Platooning *Geometrical Design and Surrounding Infrastructure*

5. Supervision

Supervisor **Kelly Pitera**

Standardized supervision time is **25 hours** for 30 credits (siv.ing) and **50 hours** for 60 credits (MST) theses.

6. Thematic description

Finding challenges and issues with today's road design manuals regarding autonomous truck platooning, where geometrical design, lane marking and signage are some of the most important factors.

7. Other Agreements

Supplementary agreement	**Not applicable**
Approval required (REK, NSD)	**Not applicable**
Risk assessment (HES) done	**Not applicable**

Appendix (list)

8. Signatures

Conditions	Date	Signatures
I have read and accept the guidelines for MSc theses	15.01.2018	[signature] Student
I take the responsibility for the supervision of the student in accordance with the guidelines or MSc theses	18.01.2018	[signature] Supervisor
Department/Faculty approves the plan for the MSc thesis	18/1-18	Elin Tonset Department/Faculty

Interview

Opening Questions

1. What is your background/experience? How are you involved in the work related to automation?
    - More than 10 years working experience within the domain of C-ITS and 4 years with Automated Driving

Main Questions

Truck related questions

2. To your knowledge, what is the state of automation of your company's trucks?
    - This OEM is in a leading position as we are developing the most desirable products on the market.
3. In your opinion, will automated trucks have the same shape and dimensions as today's conventional trucks?
    - There will be a lot of new innovations regarding to this and depending to different use cases there will be products with other shapes and dimensions on the market.
4. What's the expected weight/power ratio with a fully loaded autonomous truck? Does this vary from today's conventional trucks?
    - The weight and power regulation will be applicable to AD trucks as well. AD will certainly open up new possibilities which may have impacts on the current regulation.
5. How does automated trucks operate differently than today's conventional trucks? (Behavior, acceleration, braking, staying within the lane, …)
    - The aim of AD is to eliminate the risks taken by human driver and by that we would say that AD will be more safe and secure.
6. Do you have an expected target for how fast your automated trucks will react (reaction time)?
    - The target is to put a completely safe product on the road, nothing less than that. By this the reaction time should fulfill all safety aspects.
7. Daimler stated that they used a 0,1 second safety margin during European Truck Platooning Challenge 2016. In your opinion, is this a plausible reaction time if the system is on-board?
    - The time gap can varies depending to the current traffic situation. We are focusing on an absolute time gap but also a safe one.
8. How will a truck platoon be different from a single autonomous truck? (related to the questions above: behavior, performance, reaction)

- A platoon, as a System of systems, needs to consider the state of the Platoon systems which is not the case for a single autonomous truck.

Road design

9. Have you encountered any limitations of your automated trucks related to the roads themselves? (Narrow roads/lanes, bridges, tunnels, sight of distance, slopes, corners, standard of road/markings/signs)
    - Increased quality of sign and lane marking is always on the wish list. Otherwise a harmonization of standards regarding to different type of road is required. The level of digitalization and frequency of updates of road information need to be improved.
10. As you see it, what are the challenges for the road infrastructure, assuming your trucks work flawlessly? Are road markings needed? How does the weather affect the technology (ice or snow-covered roads)?
    - Road marking is certainly an important aspect of the road but it is not the only source of information. Availability of digital and accurate map and positioning is even more important. Other challenges are the identification of AD zones with completion of other facilities for exchange of AD to manual driving.
11. Will platoons be any different than single automated trucks regarding physical limitations and challenges such as wear or weather conditions? (Related to questions above)
    - Not much than Platooning requires even more space and visibility for safe maneuvering.
12. Do you have any requirements/lower standard for where platooning can function without de-coupling? (alignment radius, gradient, widths, specific speed) Or if it’s easier, do you have any specific places you have to de-couple?
    - The most challenging part for Platooning is the management of Entrance/Exist on the highway where the risk for de-coupling is higher.
13. Do you think there will be any problems for a platoon being used on 2-lane road? Why?
    - Not, there will not be a major problem with increased longitudinal and lateral control.
14. Your company participated in the European Truck Platooning Challenge. Related to the infrastructure: Did you have to de-couple at certain road elements or traffic conditions? Did you find any specific problems with the infrastructure?
    - The availability of I2V would have improved the management of some road segments where interaction with infrastructure and other vehicles would resolve the situation and increased safety aspects. Lack of these features lead to de-coupling of the platoon.

Sensors

15. What types sensors do your automated trucks use now?
    - At this stage we are using different sensors such as radar, lidar, camera and DSRC
16. How do you expect the sensors to evolve? Do you think the same sensors will be used in 20 years or are there some other rising technologies that look promising?
    - The rapid development in this area make it hard to anticipate what would be available in 20 years. The combination of sensor, GPU power and V2X technologies will certainly bring it new solutions which is completely unknown today.
17. How does automated trucks handle tunnels or cities with high-rises? Are there problems with regards to positioning? Do these places need extra infrastructure or is on-board technology enough to ensure safe functionality?
    - Accurate positioning is a must and unfortunately it is even worse when you absolutely need it (e.g. tunnels, high density area and so on). Implementation of I2V would certainly improve the current situation specially in the mentioned area.
18. Do you need highly detailed digital maps or something similar for the trucks to function? Why not?
    - Yes, identification of all possible routes and details is very important in path planning.
19. Are your trucks processing everything on-board or is it done through some sort of "cloud"-based system? Do you think it will be this way in 20 years?
    - The real-time and level of integrity aspects on safety related feature does not give any other alternative than doing everything on-board. Cloud based systems as assistance in pre-trip and post-trip phases is certainly interesting but not critical for AD.