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Case Studies on Infrastructure, Organization, Technology and Economics

Doctoral thesis

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Norwegian University of Science and Technology
Thesis for the Degree of
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Summary

Due to the intrinsic properties of the trucking industry, road freight is predicted to be an early adopter of highly automated vehicles on open roads. As a step towards fully driverless trucks, truck platooning is among the solutions which are forecast to materialize first. Leveraging the benefits of human supervision and automated driving, truck platooning refers to the idea of wirelessly connecting trucks, so they partake in coordinated convoying behind one another.

Truck platoons are currently manned by a driver in the lead truck, who drives it manually. There are also safety drivers in the following trucks, who may be in charge of lateral control. The following trucks use automated distance-keeping systems to regulate speed, maintaining a preset distance to the preceding truck. Platooning with wireless communication may allow for short following distances since the reaction times of human drivers must no longer be accounted for. Hence, platooning may yield fuel savings and increased traffic safety. While all trucks in a platoon are required to be manned today, following trucks may eventually become unmanned. Then, the platoon could be controlled or monitored only by the lead driver, as digital systems could transfer his or her driving commands rearwards. This could allow for a doubling, or more, of per-driver freight volumes, which could reduce costs and alleviate driver shortages. Motivated by these prospects, platooning has been extensively researched in countries with favorable infrastructure, typically on multilane motorways.

Limited research has considered truck platooning on typical Norwegian freight routes, which are predominantly two-way, two-lane rural roads, often characterized by difficult geometry, tunnels and ferry crossings. Moreover, previous research on organizational aspects of truck platooning is of limited relevance to the scattered industrial structure which characterizes Norway. Truck platooning depends on the simultaneous presence of at least two trucks to form a platoon, but it is unclear if the demand for road freight in Norway is sufficient to enable their organization at scale. Norway is also a small market for truck manufacturers, so they may not be willing to exert the effort to ensure that their systems work well on Norwegian roads. On the other hand, Norway is an affluent and technologically proactive nation with favorable regulation for testing automated driving systems. Still, fully driverless trucks on Norwegian roads seems far off, and it should be explored whether the prospects from platooning found in previous research may materialize in Norway. Local conditions may also give rise to novel motivations and unlock new avenues for implementing truck platooning.

This doctoral thesis explores enablers and barriers for truck platooning, seeking to establish whether it constitutes a promising solution for road freight in Norway. Consequently, it is the first piece of work to publish peer-reviewed studies on the applicability of truck platooning in Norway from a transportation engineering perspective. The thesis may also serve as a state-of-the-art on higher-level automated trucks, and for automated vehicles generally, in the Norwegian context. Three separate case studies were undertaken as part of the doctoral work, namely a *Stakeholder Study (i)*, a *Field Study (ii)*, and an *Industrial Study (iii)*.

i. The *Stakeholder Study* explored the viability of truck platooning by interviewing professionals and practitioners in the transport sector. Novel deployment scenarios were outlined, including the use of ferry terminals for coordination, and envisioning

truck platooning as a northward extension of the rail freight service. Interviewees stated that truck platooning will represent a mindset shift for carriers, as it requires them to cooperate. Truck platooning may be most feasible on long shipments which traverse high-standard roads with sufficient numbers of trucks to minimize the time spent waiting for a partner. Platooning may also warrant increased road maintenance spending, particularly if the value of transported goods were to be included in cost-benefit analyses. From an economic outlook, platooning may not be adopted until following trucks are unmanned and labor costs are unlocked.

ii. The *Field Study* provided realistic, hands-on experience with truck platooning on a difficult rural road, using trucks with a prototype platooning system. The trucks were instrumented to study how the platoon behaved throughout the drive. The drivers were responsible for steering, while longitudinal control was automated. Most driving was uneventful, but the system was occasionally unable to keep the platoon stable in areas with sharp curves and rolling hills. In such situations, drivers occasionally had to intervene by pressing the brake and accelerator pedals. More advanced platooning systems with wireless communication should be tested, as these may overcome the aforementioned barriers, making it easier to draw conclusions on the operational viability of truck platooning in Norway. Truck manufacturers and data scientists should also be involved in piloting efforts to streamline data collection and analysis.

iii. The *Industrial Study* complemented the prior studies by exploring two state-of-the-art trucking automation projects in closed areas. By interviewing project managers, the study reflected on the extent to which their experiences may suggest development paths for automated trucks on open roads. While the operations are impressive, the interviews revealed that both use-cases are highly customized, and hence simple, compared to the requirements for systems intended for public roads. Specifically, many technical issues had been circumvented using organizational and infrastructural means which are hard to undertake elsewhere. Based on experiences from the use-cases, the study also discussed the removal of safety drivers.

The case studies indicated that deployment of truck platooning requires efforts across four interwoven themes, namely conventional infrastructure, organization, enabling technology, and economics. Once the technology matures, truck platooning may be facilitated by certain aspects of Norwegian road infrastructure, while others will hinder deployment. Homogenous, high-standard roads seem most feasible, but freight corridors with such properties are limited in Norway, comprising a barrier. Conversely, many destinations in Norway have few alternative routes, causing natural funneling of trucks, which may support platooning arrangements. Ferry terminals, customs offices, and hubs along main roads, may comprise locations from where platoons can depart. High asset turnover among carriers may also expedite the uptake of new technology. Tunnels and winter conditions seem to pose operational challenges. Truck platooning still faces many unanswered questions, warranting further research. Until these are better understood, freight solutions should be explored which play to our strengths across all modalities, and which harmonize well with the Norwegian industrial structure.

Sammendrag

Tungtrafikken er spådd til å være tidlig ute med å ta i bruk automatiserte kjøretøy på offentlig veg, grunnet flere egenskaper som kjennetegner lastebilnæringen. Som et steg i utviklingen anses truck platooning som en av løsningene som forventes å dukke opp først. Konseptet søker å kombinere fordelene med menneskelig tilsyn og automatisert kjøring, og går ut på å trådløst koordinere og koble sammen grupper med lastebiler i kortesjer langs vegen.

Truck platoons styres manuelt av en sjåfør i fremste lastebil, mens de påfølgende lastebilene er utstyrt med automatiserte systemer som opprettholder en forhåndsdefinert avstand til den forankjørende. Sjåførene i bakenforliggende lastebiler kan ha ansvar for svingebevegelser, men svingebevegelsene kan også være automatiserte, slik at sjåførene i praksis opptrer som sikkerhetssjåfører. I fremtiden kan de bakenforliggende lastebilene bli helt førerløse. Trådløs kommunikasjon kan overføre kjørekommandoene fra sjåføren i den fremste lastebilen, direkte til styringssystemet i de bakenforliggende lastebilene. Platooning kan dermed legge til rette for korte følgeavstander, siden reaksjonstidene til de bakenforliggende sjåførene ikke lenger må tas hensyn til. Bakenforliggende lastebiler kan dermed bli liggende i dragsuget til sin forankjørende lastebil, og dette kan utløse drivstoffbesparelser. Samtidig kan platooning med førerløse lastebiler bakover i kortesjen øke mengden last som hver sjåfør kan frakte. Med bakgrunn i disse mulighetene har truck platooning vært gjenstand for mye forskning i land med godt egnet infrastruktur, og mye testing har funnet sted på motorveger.

Det finnes lite forskning om platooning på typiske norske godsruter, som hovedsakelig er landeveger, ofte preget av krøkkete geometri, lange tunneler, samt fjell- og ferjeoverganger. Tidligere betraktninger om organisatoriske aspekter ved truck platooning er dessuten lite relevant for vegsystemet og den spredte næringsstrukturen som kjennetegner landet vårt. Truck platooning krever tilstedeværelse av minst to lastebiler samtidig, men Norge er preget av forholdsvis lave trafikkvolumer. Dette kan gjøre det vanskelig å organisere truck platooning. Norge er dessuten et lite marked for lastebilprodusentene, slik at de ikke nødvendigvis er interesserte i å tilpasse sine kjøresystemer for norske forhold. På den annen side er Norge en velstående og teknologisk proaktiv nasjon med gunstig lovgivning for testing av automatiserte kjøresystemer. Til tross for dette vil det sannsynligvis ta lang tid før helt selvkjørende lastebiler er pålitelige nok til å begynne å trafikkere det norske vegnettet. Det bør derfor undersøkes om utsiktene for platooning identifisert i internasjonal litteratur kan oppnås i Norge. Kanskje kan også lokale forhold gi opphav til nye motivasjoner og muligheter for å ta i bruk platooning.

Denne avhandlingen studerer truck platooning for å forstå i hvilken grad konseptet kan være aktuelt i landet vårt, og er den første som inneholder fagfellevurdert vegfaglig forskning om truck platooning i Norge. Den danner også et grunnlag for videre arbeid med innføring av automatiserte lastebiler og kjøretøy mer generelt, i norske forhold. Avhandlingen er basert på tre studier, en *Interessentstudie* (i), en *Feltstudie* (ii) og en *Industristudie* (iii):

i. *Interessentstudien* utforsket hvorvidt truck platooning er egnet i Norge. Intervjuer ble avholdt med fagfolk som beskjeftiger seg med godstransport på veg. Fiktive, lokalt inspirerte scenarioer ble brukt for å engasjere deltakerne til å tenke over muligheter og barrierer. Informantene var enige om at truck platooning ville innebære store

endringer for transportørene, hovedsakelig fordi det fordrer samarbeid for å fungere. Truck platooning ble vurdert til å være mest egnet på lange transporter på veier med høy standard, hvor det samtidig ferdes mange andre lastebiler. Deltakerne foreslo også at verdien som godstransporten står for bør hensyntas bedre i kost-nytte vurderinger i forbindelse med oppgraderinger av vegnettet. Dette kan også tenkes å gi bedre kår for platooning. Det vil sannsynligvis ikke være regningssvarende for transportørene å ta i bruk platooning før bakenforliggende lastebiler kan bli førerløse.

ii. *Feltstudien* innebar testing av truck platooning på åpen veg med tre lastebiler, og høstet praktisk erfaring på en krevende vegstrekning i Nord-Norge. Lastebilene ble instrumentert for å studere hvordan platoonen oppførte seg underveis. Sjåførene styrte rattet selv, mens avstanden til forankjørende var automatisert. Mesteparten av kjøringen gikk rolig for seg, men platoonen slet med å holde seg samlet i områder med krappe horisontalkurver og kupert terreng. Dette medførte at førerne tidvis fant det nødvendig å gripe inn, hovedsakelig ved bruk av gass- og bremsepedaler. Systemer for platooning med trådløs overføring av kjørekommandoer bør testes. Slike systemer kan tenkes å overkomme flere av utfordringene som ble observert, og dermed gi et riktigere bilde av egnetheten til truck platooning i Norge. Lastebilprodusenter bør også være aktive bidragsytere i nye studier, for å forenkle uthenting og tolkning av data.

iii. *Industristudien* gav en ny vinkling til arbeidet ved å besiktige to ulike bruksområder med automatiserte lastebiler på lukkede områder. Intervjuer med prosjektledere ble brukt for å kartlegge erfaringer fra de to prosjektene. Videre reflekterte studien over i hvilken grad erfaringene deres kan overføres til å ta i bruk automatiserte kjøretøy på offentlig veg. Selv om begge applikasjonene er å anse som nybrottsarbeid, kom det frem i intervjuene at de er relativt enkle, sammenlignet med kravene som vil møte automatiserte kjøresystemer på åpne veger. Eksempelvis ble tekniske utfordringer løst med organisatoriske endringer og fysiske tilpasninger som vanskelig lar seg overføre til veger som er åpne for allmenn ferdsel. Basert på erfaringer fra prosjektene diskuteres også betraktninger knyttet til fjerning av sikkerhetssjåfører.

Innføring av platooning og automatisert kjøring vil kreve samordnet innsats på tvers av fire overlappende temaer. Disse var veginfrastruktur, organisering, muliggjørende teknologier og økonomi. Enkelte aspekter i Norge vil legge til rette for platooning, mens andre vil gjøre det krevende å ta i bruk. Veger med høy standard virker best egnet for platooning, men godsruter med slike egenskaper har begrenset utstrekning. Mange destinasjoner i Norge har få rutevalg, slik at lastebilene samles. Fergeterminaler, grenseoverganger og andre knutepunkter kan være egnede for koordinering. Hyppig utskifting av kjøretøy blant transportører kan også fremskynde bruken av platooning. Smale tunneler og vinterforhold ser ut til å gi driftsmessige utfordringer. Platooning er fremdeles forbundet med mange ubesvarte spørsmål, og det er behov for videre forskning for å sikre tilstrekkelig modenhet gjennom alle fire temaene. Det bør samtidig forskes på utvikling av helhetlige godsløsninger som underbygger våre styrker på tvers av alle modaliteter, og som harmonerer godt med norske forhold.

Preface

Ever since I was a kid, I was encouraged to be curious, and I became compelled to explore and understand phenomena which others seemed to take for granted. Since then, I have sought challenges which have kept me on edge. This has included pursuing my high school education through the International Baccalaureate program, and obtaining my civil engineering degree from NTNU, with an exchange year at the University of California at Berkeley. This doctorate is the latest element in this repertoire.

For as long as I can remember, I have been particularly fond of road transport. This is presumably an innate passion stemming from a suburban upbringing, and a youth which happened to coincide with the seemingly never-ending Fast and Furious franchise. During my undergraduate in 2015, I remember gazing over the edge of the glass railing at the *1-Altitude Gallery & Bar* in Singapore. While dusk turned to darkness, almost 300 meters above the sparkling metropolis, I was watching the miniature cars and trucks below, as they sped past one another on the motorway. While my companions sat on lounge chairs listening to the club music, I saw the interchanges in the distance connect to one another. I imagined where the vehicles traversing them had been previously, and where they might be heading next. I liken the road network to the cardiovascular system of humanity, whereby motorways, roads and streets are the arteries, veins and capillaries, and vehicles are the blood cells that operate within them, allowing the organism of humanity to thrive, giving rhythm and life to the built environment. For me, the road transport system represents a symbiosis of the *ingenuity* of the human spirit, with the *power* of machines for propulsion, allowing people to live and work wherever they please, and for industry to engage in commerce across distant marketplaces.

The prospect of automating road freight is both exciting and mildly terrifying. Hence, the job announcement for this doctorate immediately drew my attention. Over the past years, I have had the possibility to explore technologies and issues which are likely to shape our collective future materially over the coming decades, and I believe that I have the skillset to contribute constructively to such efforts in future ventures. While the work herein has focused on road freight, automation is permeating all facets of modern life, and the process of understanding these transformations has similarities across disciplines.

Requiring both technical deep-dives and project management skills, this has truly been a formidable undertaking. The doctoral process has cemented in me the importance of being inquisitive, and to look for ways to connect experiences across disciplines. It has also instilled in me an appreciation for the hardships associated with creating knowledge. Research must be one of the more complicated professional ventures out there, regarding the scale and scope of challenges which it entails, the variety of skillsets it requires, and the extent to which it affects the mind and personal life. Hats off to others who have undergone the same process, and to those who are considering doing so in the future.

Trondheim, June 2024
Markus Metallinos Log

Acknowledgments

This publication is the culmination of four years of doctoral research, the start of which coincided with the outset of the covid-19 pandemic. The work was undertaken under the guidance of main supervisor Prof. Trude Tørset at the Department of Civil and Environmental Engineering, whose advice has been appreciated. Co-supervisor and senior principal engineer, Tomas Levin, PhD, at the Department for Transport Development at the Norwegian Public Roads Administration, has also been influential, particularly through his suggestions for research directions. The same is true for co-supervisor Prof. Kelly Pitera, now at Oslo Metropolitan University. Jan Erik Molde at the Department laboratory was instrumental in organizing practical matters. I would also like to thank all interviewees who contributed, and the Norwegian Public Roads Administration for financing the research.

This dissertation presents three specific research initiatives, subsequently termed case studies. All were designed and executed in close collaboration with doctoral candidate Maren R. H. Eitrheim at the Department of Civil and Environmental Engineering, and at the Institute for Energy Technology (IFE). Hence, this thesis can be regarded as the first installment of an interdisciplinary project with partly overlapping objectives. As a psychologist, her research interests are human factors, meaning the interactions between humans and technology. As a transportation engineer, mine are the interactions between infrastructure, vehicles, and technology. As our tenure progressed simultaneously, collaboration with Eitrheim has contributed meaningfully to the current work. It also affected the direction of the research, both with respect to areas of interest, but not least through the widespread use of qualitative research methods. Eitrheim has contributed with a realistic, solid understanding of the strengths and weaknesses of automated systems, and of the issues which can arise when humans are tasked with overseeing them. Hence, the work has taken a more human-oriented approach than what a traditional civil engineering thesis presumably would have.

Thanks to my extended family for assisting with independent inspection of draft versions of all publications, including this one. Especially my sister, Alexandra, has provided instrumental advice and motivation, particularly in the final innings of the doctoral work. A word of appreciation is also warranted for my colleagues that, through playful banter, livened many difficult moments over these years. I would like to explicitly call out Dip (Dipanjan Nag). I will sincerely miss our collegial companionship. Finally, thanks to my kind-hearted grandmother, Karla, for always being supportive. I know that you have been waiting patiently to read this book. Hopefully it meets your expectations!

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Nomenclature

Table i. SAE Levels of automation (SAE International, 2021; Xue et al., 2018).

Level	Description
0	The driving automation system provides only warnings and momentary assistance, such as blind spot and lane departure warnings. The driver is in charge of the entire driving task.
1	The driving automation system provides either lateral or longitudinal support, such as lane-keep assist or adaptive cruise control, respectively, but not both simultaneously. The driver is in charge of the driving task.
2	The driving automation system provides both lateral and longitudinal support, such as lane-keep assist and adaptive cruise control. The driver is in charge of the driving task.
3	The vehicle operates without human input or supervision under limited conditions, for instance only during slow-moving, congested traffic on motorways. If the conditions are not met, the driver must take over (fallback).
4	The vehicle operates without human input or supervision in limited conditions, but the vehicle is capable of fallback and hence will not require a driver.
5	The vehicle operates without human input or supervision in all conditions.

Table ii. Abbreviations used in the current work. Inspired by Schoettle & Sivak, (2017).

Abbreviation	Definition
ACC	Adaptive Cruise Control
EMS	European Modular System
GNSS	Global Navigation Satellite System
ITS	Intelligent Transport Systems
Lidar	Light Detection and Ranging
LKA	Lane-Keep Assist
LDW	Lane Departure Warning
NPRA	Norwegian Public Roads Administration
NTNU	Norwegian University of Science and Technology
ODD	Operational Design Domain
OSL	Oslo International Airport
Radar	Radio Detection and Ranging
RTK	Real-time kinematic (GNSS corrections)
SAE	Society of Automotive Engineers
VAS	Volvo Autonomous Solutions

Table iii. Glossary of commonly used terms. Inspired by Axelsson et al., (2020).

Term	Definition
Automated Driving System	The combination of hardware and software which facilitates automated driving at higher SAE levels (i.e., 3-5) (Storsæter, 2021).
Carrier	Trucking company (Caballini et al., 2016).
Driving automation system	The combination of hardware and software which facilitates automated driving at any level of the SAE scale (i.e., not just 3-5).
EMS road train	A rigid truck pulling a semi-trailer behind it, with maximum length 25.25 m, subject to a handful of permitted configurations.
Freight mode	The type of transport used to deliver goods. These are typically road (trucks), air (planes), rail (freight trains) and sea (ships).
Gap	The temporal spacing between two successive trucks, from the front-end of the rearmost truck to the rear of the preceding truck.
Headway	The temporal spacing between two trucks, from the front-end of the rearmost truck to the front-end of the preceding truck.
Inter-vehicle distance	The geometric distance (in meters) between two successive trucks (K. Wang et al., 2022). The term is synonymous with *separation distance* or *clearance* (Isarsoft, 2023).
Lead time	The transit time for a truck carrying goods on behalf of a shipper.
Tractor	A truck (without cargo space) made for pulling a semi-trailer.
Truck	A combination of a tractor and a semi-trailer.
Two-way, two-lane road	Road with a total of two traffic lanes, serving traffic headed in opposite directions without physical barriers
Semi-trailer	A trailer which requires its front-end to be attached to a tractor.
Shipper	Companies which make or supply goods which need to be shipped.

1 Introduction

This chapter describes the motivation behind the research, clarifies the scope, and formalizes the research questions which guided the work. It also provides an overview of the case studies which were undertaken, and the contributions of the doctoral work towards the greater body of knowledge on truck platooning.

1.1 Motivation

This work is motivated by postulated benefits related to emerging trends and concepts in vehicle automation. As research on this topic has mostly been undertaken else-where, there is a need to understand how these concepts may be adapted to the specific Norwegian context. Since "*the benefits of new technology will not necessarily realize them-selves*" (Handberg et al., 2024, p. ii), this suggests the need to study the road freight eco-system, and also possibly adapt regulations and infrastructure.

1.1.1 Trends and Concepts

Automated driving features are becoming increasingly commonplace in the vehicle fleet, and trucks are no exception (Engström et al., 2019; Poorsartep & Stephens, 2015). The trucking industry is believed to be among the first sectors where driving automation will become commercially available (Tsugawa et al., 2016), and some expect widespread deployment of automated trucks by the 2040s (Litman, 2023). Others suggest that automated trucks, due to their weight and dimensions, may require large infrastructure amendments, compared with automation of passenger vehicles (Ulrich et al., 2020). This alludes to slower, and perhaps also more localized deployment, potentially unlocking fewer benefits (Geißler & Shi, 2022). These conflicting viewpoints regarding the temporal and spatial introduction of automated trucks, provide an interesting backdrop for the current work.

Automated trucks may take on many forms (Shladover, 2010). While technologically difficult, singular trucks could be highly automated, each one operating as a free agent (Tsugawa et al., 2011). In theory, such trucks could comprise self-contained systems, capable of self-driving without centralized control (Urmson et al., 2008). While such prospects are alluring, many companies attempting to develop fully self-driving trucks have struggled in the past years due to technical challenges (Glasner, 2022), and industry expectations for automated vehicles seem to have cooled down in general (Siren, 2021, p. 2). Consequently, truck platooning poses an interesting proposition. As a stepping-stone to full autonomy, trucks can be virtually linked into *platoons*, meaning convoys or strings of trucks which drive in a coordinated manner closely behind one another. By definition, platoons consist of one lead truck and one or more following trucks. Using adaptive cruise control (ACC) and wireless technology, the trucks form a train on the road (Shladover, 2010; Siren, 2021, p. 5; Ulrich et al., 2020; L. Zhang et al., 2020).

Platoons are conceived of as an early form of automation in an open environment (Bhoopalam et al., 2018; Tsugawa et al., 2016), benefiting from the on-site presence of at least one human driver. Specifically, platoons are envisioned to be operated by a driver in the lead vehicle, while the following trucks are either manned by drivers who are in charge of the steering wheel, or who serve as safety drivers, overseeing the automated system. In the future, the following trucks may be remotely operated from control centers, or they could be fully driverless. This contrasts present-day trucking, where each driver is in charge of driving, and the trucks are operated independently from one another (Axelsson, 2017). The term platooning is also used in the context of other vehicles, but the truck application is most prevalent (Axelsson, 2017). Since platooning is forecast to materialize earlier than free-agent automation, it constitutes the main operational concept of this doctoral work. However, free-agent trucking automation was also studied, so some reflections for higher-level automation are also provided.

1.1.2 The Norwegian Context

Norway is well-positioned for adopting automated vehicles, due to widespread and high-quality cellular coverage, a favorable regulatory environment, and coordinated efforts across government and industry for conducting field trials (KPMG International, 2022, p. 14). The Norwegian road network is also at the European forefront in implementation of Intelligent Transportation Systems (ITS), referring to the use of digital technologies, automated processes and wireless exchange of information to enhance traffic safety and traffic flow (Dysvik & Bjørkås, 2021, pp. 38–39). Moreover, the world-class adoption of electric vehicles in Norway may serve as a proxy for the willingness of Norwegian individuals and organizations to adopt automated vehicles (KPMG International, 2022, p. 14). Since truck platooning is a subset of automated vehicles, many of these aspects may also translate into favorable conditions for adopting truck platooning. The Norwegian economy relies on trade with foreign nations, and a large part of this trade depends on road freight. These attributes suggest that platooning could represent a promising solution for streamlining the Norwegian trucking industry.

Conversely, deployment of automated vehicles and truck platooning in Norway may be more challenging than deployment in other countries. Specifically, aspects such as harsh weather, and the prevalence of rural two-way, two-lane roads, may comprise barriers. While Norway is affluent and technologically proactive, the nation is also geographically peripheral, with low overall truck volumes. Hence, despite road freight being an international industry, potential introduction of truck platooning elsewhere may not translate into similar adoption in Norway. Norway also has no local vehicle manufacturing (Yan & Eskeland, 2018), so its local conditions may not be sufficiently accounted for in the development of driving automation systems, as such systems are mostly developed in other countries and tailored to generalized vehicle markets.

Even if deployment were to be successful from a technical perspective, some policymakers believe that the characteristics of the Norwegian context may result in fewer benefits being unlocked from platooning than if it were to be deployed elsewhere (Vartdal et al., 2020, pp. 23–24). The consequences of automated vehicles in Norway were mapped in Nenseth et al., (2019), and in the so-called Oslo study (COWI, 2019). These reports, however, did not consider road freight. Hence, unanswered questions remain both related to the viability, and the usefulness, of truck platooning in Norway.

1.1.3 Adaptations for Automation

Some Norwegian policymakers are skeptical of truck platooning due to road standard (Vartdal et al., 2020, pp. 23–24). As road standard is the domain of roads authorities, such statements imply that these organizations may serve as facilitators for truck platooning and vehicle automation.

The Norwegian Public Roads Administration (NPRA) is an important roads authority in Norway. It governs standards for road design, operates the network of national roads, regulates traffic on all public roads (Norwegian Public Roads Administration, n.d.-c, n.d.-d), and oversees research on all open roads pertaining to vehicle automation (Lovdata, n.d.-b). The NPRA has also led and participated in many research initiatives (e.g., Arnesen et al., 2021; Gómez-Belinchón, 2023; Klingenberg, 2018; Norwegian Public Roads Administration, 2022). There are also other types of public roads owners in Norway. Compared to the NPRA, however, these agencies are involved to a lesser extent in research activities and development of regulations related to vehicle automation. They are also involved to a lesser extent in developing regulations which may affect driving automation levels. Nevertheless, all agencies in Norway which own and operate public roads have the ability to affect the operational conditions for driving automation systems (Storsæter et al., 2021b).

Specifically, conditions for driving automation systems can be simplified through investments and maintenance practices. For instance, roads agencies may strive to ensure homogenous road standard (Geißler & Shi, 2022). Automation is forecast to tighten the link between vehicles, infrastructure and digital systems (OECD Publishing, 2023, p. 8). This entails a shift for roads authorities. Human driving abilities have traditionally provided the conditions for road design and maintenance. In the future, however, these may increasingly be governed by the capabilities of driving automation systems (Storsæter et al., 2021b, 2021a). Eventually, automation may warrant changes to aspects such as road design and speed limits (Farah et al., 2018; Storsæter et al., 2021b). The term *Operational Design Domain* (ODD) (Lee et al., 2020; Llorca, 2021) is used to denote situations where driving automation systems are safe to use, including aspects such as the vehicle, the road, digital connectivity and weather. The term is also applicable for truck platooning. Some suggest that the alignment of infrastructure to the ODDs of driving automation systems may require significant physical changes to the infrastructure (Arnesen et al., 2022; Carreras et al., 2018; Ulrich et al., 2020), along with new maintenance procedures (Storsæter et al., 2021a). Nevertheless, it is still unclear what exact features make a road automation-ready (OECD Publishing, 2023), and little effort has been put into ensuring that roads are adapted for driving automation (Storsæter et al., 2021b; Ulrich et al., 2020).

Research is needed to explore possibilities and constraints for deploying truck platooning in Norway. This includes the willingness of relevant stakeholders towards accepting its use, and the viability of the road network to support the operation of platooning systems (Cucor et al., 2022; Geißler & Shi, 2022). Since technology requires time to mature, legislation takes time to implement, and roads are built with 20-year design periods (Norwegian Public Roads Administration, 11 C.E.), necessary changes should be made at the right time, and in the right locations (Geißler & Shi, 2022), for Norway to fully capitalize on developments in truck platooning and vehicle automation.

1.2 Themes and Research Questions

The current work found that deployment of truck platooning hinges upon *infrastructural*, *organizational*, *technological*, and *economic* feasibility. These four themes were also identified by Axelsson et al., (2020), and they were used to organize the current work. While the themes are broad and somewhat indeterminate, **Table 1** provides suggested definitions, modified to accommodate the truck platooning application.

Table 1: Definitions of main themes.

Theme	**Definition**
Conventional infrastructure	The fixed component of the road transport system, including all routes and physical installations necessary (Kapur et al., 2021) for the operation of truck platoons.
Organization	The manner in which truck platooning is arranged (Cambridge University Press & Assessment, 2023). This involves concepts such as planning, coordination, administration, and management.
Enabling technology	Technologies arising from science and engineering activity that facilitate driving automation systems. Enabling technologies tend to have platform-like features, meaning they are typically owned as intellectual property (Teece, 2016), and licensed by downstream customers , e.g., carriers. The term is mostly used here to refer to sensors and digital back-end systems, which may also be termed "invisible infrastructure" (OECD Publishing, 2023; Tsugawa et al., 2016).
Economics	The costs and savings associated with deploying and operating truck platoons, and secondary effects on pricing for shippers.

The themes may be conceived of as umbrellas under which multiple *factors* reside, and factors are components which affect the feasibility for platooning. As the themes are interconnected, viewpoints may differ regarding which theme each factor belongs to. **Figure 1** shows factors which were found to be important for deployment of truck platooning in Norway, and under which theme they were organized. For example, maps could constitute both *Infrastructure* and *Technology*, but it is here conceived of as the latter, since readers may to associate the term *Infrastructure* with physical road design elements. Requirements for themes and factors may change due to developments in others. The structure does not consider aspects such as weather and external traffic, but when discussed, it is done in relation to the most relevant theme. The factors shown in **Figure 1** provided a solid foundation for addressing the research questions.

Based on the four identified themes, the following research questions were formulated:

RQ1. What infrastructural factors facilitate or hinder deployment of truck platooning on public roads in Norway?

RQ2. What organizational factors facilitate or hinder deployment of truck platooning on public roads in Norway?

RQ3. What enabling technologies are needed for truck platooning on public roads in Norway?

RQ4. What economic considerations facilitate or hinder deployment of truck platooning on public roads in Norway?

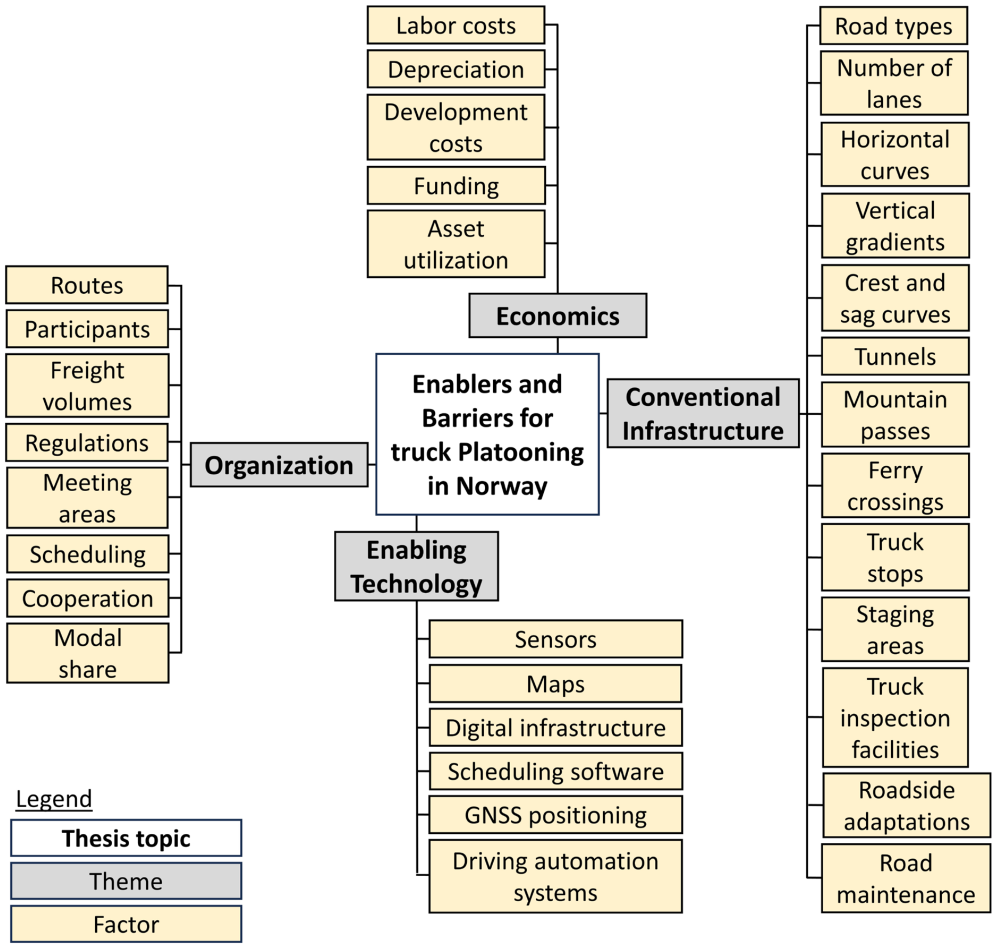

Figure 1: Overview of themes and important factors.

1.3 Case Studies

The research questions were addressed using three self-standing case studies. Based on these case studies, four research papers were written. Capitalized letters are used throughout the thesis when referring to these specific case studies and papers. The relationship between the case studies and the papers are described below:

1. The potential implementation of automated trucks on public roads is a complex and interdisciplinary undertaking, hinging on concerted efforts by many stakeholders, such as road operators, regulators, shippers, carriers, and truck manufacturers. Hence,

it was necessary to establish a high-level overview of the relevant actors in the playing field, and to understand the extent to which they could envision truck platooning as a useful addition to the Norwegian road freight system. This was done through a *Stakeholder Study,* which involved interviewing a range of actors knowledgeable in road freight. This study resulted in the publication of Paper 1.

2. It was considered useful to gain first-hand experience with a state-of-the-art truck platooning system in realistic Norwegian conditions. This was done in a *Field Study*, which culminated in Papers 2 and 3. The former paper details the use of aftermarket radar and camera equipment to measure inter-vehicle distances between the trucks, as such data were not available from in-vehicle sensors. The latter paper presents general findings from the Field Study, focusing on operational and infrastructural readiness for the truck platoon.
3. Following learnings from the Field Study, industrial areas emerged as a domain where automated driving systems seemingly had become more sophisticated, in terms of partaking in real-life commercial operations. Experiences from industrial trucking automation projects may suggest future developments in on-road automation, including truck platooning. Hence, an *Industrial Study* was undertaken to explore the state-of-the-art on automated trucks in Norwegian conditions. Using interviews, the Industrial Study explored two such use-cases, and reflected on the extent to which identified learnings were transferrable to the public roads sector. The Industrial Study resulted in the publication of Paper 4.

1.4 Scope

The following subchapters describe the characteristics which delimit the boundaries of the current work, mainly with respect to time frame and levels of automation. Finally, it showcases typical aspects of truck platooning research which are not considered herein.

1.4.1 Time frame

This thesis aims to generate pragmatic knowledge on the viability of platooning in Norway, to support the prioritization of future research efforts. The current state of the road network was used as a baseline, as recommended by Paulsen (2018), who used a theoretical approach to study road design parameters subject to platooning and automated trucks in Norway. A short to medium time horizon was chosen for the current work, referring to the next 5 to 10 years, as this would provide realistic and actionable knowledge ahead of uncertain technological developments.

1.4.2 Automation Levels

Since the thesis considers a short time horizon, driving automation systems are deliberately referred to as *automated*, as opposed to *autonomous* or *self-driving*, as the latter two suggest emergent properties of self-reliance (Dixon, 2020), which currently seem far off. Hence, the case studies were based on contemporary or near-term applications of trucking automation. Both the Field Study and the Industrial Study describe *current reality*, and the Stakeholder Study and the Industrial Study jointly elicited reflections on *future* automated driving systems. Hence, this research provides both short-term and long-term insights for policymakers to prioritize future work.

Practitioners often use the Society of Automotive Engineers (SAE) Driving Automation Levels (SAE International, 2021) to classify driving automation systems. While subchapter 2.1.1 introduces the SAE taxonomy in detail, a brief overview is provided here to summarize the scope of automated driving levels which are included in the current work.

All three case studies discussed truck platooning, albeit spanning different automation levels and operational concepts. While the Stakeholder Study always assumed the presence of a driver in the lead truck, reflections from interviewees on the applicability of platooning were occasionally provided for situations where the following truck in a two-truck platoon was both manned and unmanned, placing the follower at SAE levels 1-3 and 4-5, respectively. The trucks which took part in the Field Study were operated at SAE level 1, with only longitudinal automation. Lastly, the Industrial Study involved two industrial applications of automated trucks. One ostensibly resembled truck platooning, and the other involved free-agent automated trucking. These applications were arguably operated at SAE levels 3 and 4, respectively. Hence, this research work considered automation throughout most of the SAE scale.

1.4.3 Deliberate Omissions

The effects of truck platooning on occupants, external traffic, bridge bearing capacity and road substructure are not discussed. Urban freight challenges are also considered to be outside the scope of work, and the same is true for the effects of platooning on traffic flow, as Norwegian freight routes generally have ample capacity. While some remarks are made on the human dimension of truck platooning and vehicle automation, this was not the focus of the current work.

1.5 Contributions

This subchapter details the contributions of the current work towards the scientific literature on truck platooning.

1.5.1 Main Papers

Four papers are included in this doctoral work. These are referred to as Papers 1 through 4, as they are encountered in subsequent chapters. **Table 2** details the contributions made by the current candidate, based on the Contributor Roles Taxonomy (Brand et al., 2015).

Table 2: Overview of scientific papers which are part of this thesis.

Paper		Contributions
1	Eitrheim, Maren Helene Rø; **Log, Markus Metallinos**; Tørset, Trude; Levin, Tomas; Pitera, Kelly. (2022). *Opportunities and Barriers for Truck Platooning on Norwegian Rural Freight Routes*. Transportation Research Record. Volume 2676 (6).	Methodology, Data curation, Formal analysis, Investigation, Writing - Original Draft, Writing - Review & Editing, Visualization.
2	**Log, Markus Metallinos**; Thoresen, Thomas; Eitrheim, Maren Helene Rø; Levin, Tomas; Tørset, Trude. (2023). *Using Low-Cost Radar Sensors and Action Cameras to Measure Inter-Vehicle Distances*	Conceptualization, Methodology, Investigation, Data Curation, Writing - Original Draft, Writing -

Paper		Contributions
	in Real-World Truck Platooning. Applied System Innovation. Volume 6 (3).	Review & Editing, Visualization.
3	**Log, Markus Metallinos**; Eitrheim, Maren Helene Rø; Pitera, Kelly; Tørset, Trude; Levin, Tomas. (2023). *Operational and Infrastructure Readiness for Semi-Automated Truck Platoons on Rural Roads*. Proceedings from the Annual Transport Conference at Aalborg University (Vol. 30).	Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Writing - Original Draft, Writing - Review & Editing
4	**Log, Markus Metallinos**; Eitrheim, Maren Helene Rø; Tørset, Trude; Levin, Tomas. (2023). *Lessons Learned from Industrial Applications of Automated Trucks for Deployment on Public Roads.* Proceedings from the Annual Transport Conference at Aalborg University (Vol. 30).	Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Writing - Original Draft, Writing - Review & Editing

The contents of each paper are as follows:

1. Presents findings from interviews with various stakeholders in the Norwegian road freight ecosystem regarding the viability of truck platooning on Norwegian roads.
2. Details experiences from testing a novel radar sensor to measure inter-vehicle distances during truck platooning and presents a video-based methodology to filter such data.
3. Showcases experiences and observations from truck platooning on a difficult rural road.
4. Contains findings and reflections for on-road trucking automation based on interviews with project managers from industrial use-cases of automated trucks.

Paper 1 was accepted to the Annual Meeting of the Transportation Research Board in 2022, but the paper could not be presented there due to the covid-19 pandemic. While Paper 2 was a pure journal submission, both Papers 3 and 4 were presented at the 2023 Annual Transport Conference at Aalborg University. Subsequently, both papers were submitted to the Danish Journal of Transportation Research. In November 2023, Paper 4 was accepted to this journal, pending revisions. In January 2024, Paper 3 was accepted to the same journal outright.

1.5.2 Supplementary Papers

The candidate contributed to four supplementary papers, listed in **Table 3**. These are outside the scope of this thesis but still relevant to the broader topic. The first two papers were based on the Field Study, while the two remaining ones were based on adjacent efforts which are not described here. The Field Study also provided the basis for a master's thesis in software engineering at the Department of Informatics at the Western Norway University of Applied Sciences (Vindenes, 2022). It details all data types, alongside methods for processing and data visualization.

Table 3: Overview of supplementary papers.

Supplementary paper	Contributions
Eitrheim, Maren Helene Rø; **Log, Markus Metallinos**; Tørset, Trude; Nordfjærn, Trond; Levin, Tomas. (2023). *Driver acceptance of truck platooning: state-of-the-art and insights from a field trial on rural roads*. Proceedings of the 33rd European Safety and Reliability Conference (ESREL 2023).	Writing - Review and Editing
Eitrheim, Maren Helene Rø; **Log, Markus Metallinos**; Tørset, Trude; Levin, Tomas; Nordfjærn, Trond. (2022). *Driver Workload in Truck Platooning: Insights from an On-Road Pilot Study on Rural Roads*. Proceedings of the 32nd European Safety and Reliability Conference (ESREL 2022).	Writing - Review and Editing
Veitch, Erik Aleksander; Christensen, Kim Alexander; **Log, Markus Metallinos**; Valestrand, Erik Thule; Hilmo Lundheim, Sigurd; Nesse, Martin; Alsos, Ole Andreas; Steinert, Martin. (2022) *From captain to button-presser: operators' perspectives on navigating highly automated ferries*. Journal of Physics: Conference Series (JPCS). Volume 2311.	Methodology, Writing - Review and Editing
Namazi, Elnaz; Mester, Rudolf; Lu, Chaoru; **Log, Markus Metallinos**; Li, Jingyue. (2022) *Improving Vehicle Localization with Two Low-Cost GPS Receivers*. Innovations in Smart Cities Applications Volume 5 - The Proceedings of the 6th International Conference on Smart City Applications (SCA 2021).	Resources, Writing - Review & Editing

1.6 Structure

The structure of the thesis is summarized in **Table 4**.

Table 4: Overview of thesis structure.

Chapter		Contents
1	Introduction	Motivates the research and provides an overview of the work.
2	Background	Provides theoretical background for driving automation systems and enabling technologies behind truck platooning, alongside an overview of Norwegian road freight and infrastructure.
3	Methodology	Showcases the research design used in the three case studies.
4	Results and Discussion	Presents key results from the papers in light of the main themes and research questions and discusses and integrates the findings across the studies.
5	Limitations and Suggestions	Reflects on the thesis structure, the applicability of the research questions, and the limitations of the methods and results.
6	Conclusions	Concludes the work and recommends future research efforts.

2 Background

This chapter is organized into two main segments and provides an overview of the elements which constitute the framework of the research. Firstly, information is provided on automated driving and truck platooning, including an overview of enabling technologies. Secondly, the Norwegian context is introduced, focusing on the road network and the trucking industry.

2.1 Automated Driving

This subchapter introduces driving automation systems and taxonomies, alongside prospects for automating road freight. Previous research on truck platooning is discussed, and information is given on technologies which enable platooning and higher-level automation.

2.1.1 Taxonomies for Autonomy

Driving automation systems are becoming increasingly customary in the vehicle fleet. Vehicle sensors, digital maps, and communication between vehicles and infrastructure underpin these systems, which are presumed to constitute the building blocks of automated vehicles (Poorsartep & Stephens, 2015). The taxonomy of Driving Automation Levels by the Society of Automotive Engineers (SAE) is often used to classify the capabilities of driving automation systems (SAE International, 2021). The scale spans from manual driving with momentary warnings at the low end (SAE level 0), to vehicles being fully driverless in all conditions at the upper end (SAE level 5). While the term *driving automation system* is generic, the term *automated driving systems* is used only when referring to systems at SAE levels 3 and above (Storsæter, 2021, p. 11).

Systems at SAE level 1 are quite common. These provide either lateral or longitudinal driver support. Longitudinal control involves acceleration and braking to maintain the desired speed. Lateral control involves steering wheel movements to negotiate curves and to ensure that the vehicle stays within its designated lane (Windover et al., 2018). Adaptive cruise control (ACC) and lane-keep assist (LKA) are examples of SAE level 1 systems (Engström et al., 2019). If a driving automation system can undertake longitudinal and lateral control simultaneously, it is denoted as an SAE level 2 system. At SAE level 2, the driver remains in charge of the driving task and must supervise the system. Automakers often advertise such systems as capable of hands-free driving under specific conditions (Chevrolet, n.d.; Ford Motor Company, 2023). Systems beyond SAE level 2 are uncommon, but a few examples exist. For instance, there are systems which enable level 3 operation in traffic jams on certain motorways (Mercedes-Benz Group, 2023). SAE level 3 systems are characterized by the driver not being in charge of the vehicle once the system is enabled, but he or she must handle fallback when the system requests it. Hence, such systems require the automaker to assume liability for the driving operation during nominal driving conditions. A handful of cities in the United States and China currently have unmanned, driverless urban taxis in commercial operation, i.e., at SAE level 4. These are typically referred to as robo-taxies. These mostly operate within geofenced areas and during low-traffic periods (M. Liu et al., 2022; S. Liu & Capretz, 2021).

The SAE taxonomy is primarily designed to structure the capabilities of individual vehicles (Bhoopalam et al., 2018). This would perhaps suggest that the SAE taxonomy might not be as useful when discussing truck platooning, which are comprised of several vehicles. Two other terms are also often used in the literature on automated vehicles, namely *connected and automated vehicles (CAV),* and *cooperative, connected, and automated mobility (CCAM)*. Since these two terms explicitly include the aspect of vehicles being *connected*, they are ostensibly more applicable to truck platooning, where trucks may be automated, operate in unison and wirelessly share information (Storsæter, 2021). However, these two terms were not found to be sufficiently granular in terms of accommodating the different automation levels which were encountered in the current work. The same conclusion was reached after evaluating the three levels of human involvement in platooning, as proposed by Bhoopalam et al., (2018). Finally, the two definitions which were established in the ENSEMBLE research project were also considered. These were *platooning as support function* and *platooning as autonomous function* (Hoedemaeker, 2022). The former involves only automated longitudinal control, with drivers in all trucks, while the latter involves both longitudinal and lateral control being automated, and having a driver only in the lead truck (Siren, 2021, p. 13). However, wireless communication between the trucks is a requisite for both functions. Hence, as will be detailed in chapter 3, these definitions were not appropriate for the Field Study, nor the Industrial Study, as the trucks considered in those case studies did not have such functionality. In sum, the SAE taxonomy was used throughout the current work, as it provided the necessary flexibility for accommodating the different levels of automation which can be present in any single truck platoon. It also enabled unified discussion of all three case studies, irrespective of their automation level.

Taxonomies also exist for describing the extent to which the fixed infrastructure facilitates driving automation. Roads may be described in terms of five *Infrastructure Support Levels for Automated Driving (ISAD)*. The classification scheme is based on the availability of digital road information, and the extent to which this information is updated (Carreras et al., 2018). The lower level, E, denotes conventional infrastructure without digital information. At this level, automated vehicles must themselves read road signs and recognize road geometry. At the highest level, A (Cooperative driving), the infrastructure reports real-time information of vehicle movements in order to optimize traffic flow. Most of the Norwegian road network sits at level D, meaning it is digitized but not dynamically updated. In this thesis, truck platooning was explored with the assumption of a driver being present, at least in the lead vehicle. As this reduces the need for digital infrastructure support, the ISAD classification scheme was not considered further.

2.1.2 Automation-Enabling Properties of the Trucking Industry

This subchapter motivates the study of automated trucks, as opposed to other categories of vehicles. Specifically, the trucking industry is forecast to be early in the automation pipeline, due to several intrinsic properties:

1. Carriers are profit-driven corporations and are therefore likely to adhere to the results of cost-benefit calculations. Hence, they may be incentivized by the prospects of fuel and labor cost savings to a larger degree than what customers of passenger cars would be (Janssen et al., 2015).
2. The trucking industry is highly competitive. Hence, if automated trucks emerge, and they demonstrate increased efficiency, safety, and economic returns in early testing,

it may be difficult for companies that do not deploy such trucks to stay in business. This could result in rapid adoption (Engström et al., 2019).

3. Trucks often have predictable travel patterns (Litman, 2023, p. 5), such that the driving automation systems for trucks could be tailored to specific routes. This limits the scope of the problem, as opposed to having to account for more general and complex scenarios which are associated with passenger vehicle transportation.
4. Trucks are heavily used (Tsugawa et al., 2011, 2016), such that, even if fully or partly automated trucks were to constitute expensive upfront investments, their cost may be recouped quickly through reductions in fuel and labor cost. Automated trucks could also facilitate increased asset utilization. In the future, automation may also reduce some of the smaller cost categories which carriers face, such as maintenance and insurance (Poorsartep & Stephens, 2015), if it causes safer driving and fewer accidents (Engström et al., 2019).
5. The replacement rate for trucks is quite high. For instance, 64% of EU road freight is undertaken with trucks that are 5 years old or newer (European Commission, 2022). Hence, new technology can quickly be implemented in the fleet.

2.1.3 Prospects for Truck Platooning

Truck platoons are convoys of two or more trucks that travel conjointly, behind one another (L. Zhang et al., 2020). The first truck is presumed to have an active driver. The following truck(s) will at minimum be equipped with SAE level 1 longitudinal automation systems, where drivers are in charge of remaining parts of the driving task. Following trucks could also be outfitted with higher-level automation systems, which also account for lateral control, but still require safety drivers for occasional input. Finally, the followers could be fully automated and unmanned.

Since truck platoons are comprised of trucks, they are subject to the aforementioned automation-enabling properties which are intrinsic to the trucking industry. Note that the previous list of intrinsic properties does not differentiate between truck platooning and free-agent automation. . However, since truck platooning differs from free-agent automation, its prospects may be specified further. Previous research, as summarized in subchapter 2.1.4, indicates that truck platooning may unlock the following benefits:

1. Tuck platoons benefit from an aerodynamic phenomenon referred to as *slipstreaming* or *drafting*. The effect is sizeable for trucks, due to their boxy shapes (Gehring & Fritz, 1997; Turri et al., 2017) In fact, a quarter of fuel consumption for trucks is attributed to overcoming the resistance caused by aerodynamic drag (Turri et al., 2017). The arrangement of the trucks in close groups enables the following trucks to experience reduced air drag and thus lowered fuel consumption by approximately 10% (Sturm et al., 2021; Tsugawa et al., 2016; L. Zhang et al., 2020), leading to direct economic savings. While it may seem counterintuitive, lead trucks may also benefit from this effect, since the presence of a nearby truck trailing it reduces the turbulence behind it, and also the air friction in front of it, resulting in lower drag (Alam et al., 2015; Sturm et al., 2021). Reduced fuel consumption also leads to corresponding reductions in vehicular emissions. To unlock these benefits, however, following distances must be

very short (< 1 second). This necessitates automated steering for the following trucks, since the ability of following drivers to perceive the road environment is obstructed by the presence of the preceding truck (Nowakowski et al., 2015, p. iii).

2. In most jurisdictions, the trucking industry is subject to hours-of-service regulations, limiting the duration of driving time per day and per week. Assuming drivers are still required to oversee the operation, the order of the trucks could be switched to utilize driving time for each driver, facilitating longer-lasting operation. This would require regulatory amendments to allow in-vehicle rest while moving. Work is being done at the EU-level to change driving and rest time regulations so that following drivers actively drive fewer hours when connected in a platoon than during conventional driving (Vartdal et al., 2020). If drivers are not required in the following trucks, per-driver freight volumes may increase, which may also contribute positively towards reducing driver shortages.
3. Assuming automated driving systems become more reliable than human drivers, truck platooning may improve traffic safety (Alam et al., 2015; Engström et al., 2019; Poorsartep & Stephens, 2015; Sturm et al., 2021; Tsugawa et al., 2016). This may also provide indirect economic savings.
4. Platooning may improve working conditions for truck drivers (Engström et al., 2019; Poorsartep & Stephens, 2015), by increasing their safety, comfort and convenience (Tsugawa et al., 2016). It may therefore also help alleviate driver shortages.
5. Truck platooning may increase road capacity (Windover et al., 2018; L. Zhang et al., 2020) and improve traffic flow (Penttinen et al., 2019; Robinson & Coelingh, 2010). It may thus reduce the need for road capacity expansions (Sturm et al., 2021). In Norway, however, there is generally ample capacity in the road network for freight movements (Askildsen et al., 2023), so this prospect may be of lower importance.

2.1.4 Truck Platooning Research

Truck platooning has been widely researched in the past decades. Amongst other objectives, researchers have explored its potential for energy savings, traffic safety, and for streamlining carrier operations. Much work has also gone into exploring technical readiness. The following paragraphs are a summary of research efforts which are relevant for the current thesis.

Early Innings

Early theoretical research on the control aspects of truck platooning began in the 1960s (Turri et al., 2017). Following a hiatus, practical testing of platooning was done by Daimler-Benz AG in the mid-1990s (Tsugawa et al., 2016), with cargo vans, using a system based on cameras and wireless communication (Gehring & Fritz, 1997). Work continued through the Chauffeur research program from 1996 (Tsugawa et al., 2016). Trials have also been undertaken by the Partners for Advanced Transportation Technology (PATH) program at Berkeley (Lu et al., 2022), KONVOI in Germany from 2005-2009, and Energy ITS in Japan (Tsugawa et al., 2016).

Field Studies

Focusing on fuel savings and the development of overarching control strategies, Alam et al., (2015) undertook 30 repeated field experiments of three-truck platooning on a motorway in Southern Sweden. With respect to its proximity to Norway, this is likely the geographically closest field test from which findings were made public. The test used wireless communication and one-second time gaps between the trucks. One year later, the high-profile European Truck Platooning Challenge involved six trucks from different manufacturers platooning together on public motorways in the Netherlands (Aarts & Feddes, 2016).

Field studies have also been undertaken to explore the interactions of drivers with platooning systems in relation to driving speed, external traffic, vertical gradients, and platoon position. For instance, S. Yang et al., (2018, 2022) had drivers operate a three-truck platoon with empty trailers on motorways in Northern California. Available time gap settings were smaller than default ACC gaps from the truck manufacturer. It was found that drivers often disengaged the platooning system when driving in slow-moving traffic, and on downhills where the system was unable to provide sufficient braking force. Downgrades between negative 2.5-5% were encountered. In high-speed traffic and on uphill sections, drivers were likely to use the automated system. The authors suggest operation on routes with minimal interference to truck speeds.

The ENSEMBLE initiative is the most recently completed large-scale study on truck platooning. The project, which ended with a seven-truck demonstration on a Spanish motorway in 2022 (Zanetti, 2022), involved European truck manufacturers agreeing to the use of a standardized protocol for wireless communication. The project also established the two aforementioned definitions of platooning functions (Hoedemaeker, 2022).

Platoon Coordination

While platooning with a human operator in the lead vehicle may be technologically simpler than free-agent trucking automation, it is still a difficult technological problem. Moreover, previous research indicates that real-world truck platooning leads to increased organizational complexity, which negatively affects its business-case. Truck platooning necessitates routes with sufficient truck volumes, and hence coordination and meet-up of at least two trucks with somewhat similar destinations and physical properties (Bhoopalam et al., 2018). For example, trucks which are capable of platooning may need to wait for one another, or undertake detours or speed adjustments to join platoons (Bhoopalam et al., 2018).

The facilitation of platooning arrangements is often termed *platoon coordination*, *clustering* (Shladover, 2010; L. Zhang et al., 2020) or *matchmaking* (Gerrits, 2019), and it can either be scheduled, real-time or opportunistic (Bhoopalam et al., 2018). The former arrangement is based on static and predefined timetables. Real-time coordination is more dynamic, involving the announcement of trips by truck operators when the trucks are underway. Opportunistic matchmaking is the most dynamic method, involving spontaneous arrangements with nearby trucks. For the two latter arrangements, the probability of finding a match depends strongly on the total number of trucks on the road which are capable of platooning (Nowakowski et al., 2015). Pending increased adoption, matchmaking may best be served using static methods (Bhoopalam et al., 2018).

In this regard, the Finnish Combine project is a geographically relevant undertaking. Using a theoretical approach, it studied the viability of truck platooning as part of intermodal freight chains on a high-volume motorway between Helsinki and Tampere (Siren, 2021). Theoretical studies focusing on overarching aspects of truck platooning have also been conducted in Sweden (Axelsson et al., 2020), but thus far, no such studies have been undertaken in Norway.

Next Steps

It is generally difficult to forecast the timeline of technological disruptions. Yet, in recent years, multiple practitioners have ventured into the deep end, attempting to make projections regarding the deployment of truck platooning. In 2016, the organizers of the European Truck Platooning Challenge believed that the aforementioned demonstration would set the stage for cross-border platooning by the year 2020 (Aarts & Feddes, 2016). This projection did not materialize, alongside similar ones made around the same timeframe e.g., Chottani et al., (n.d.) and Sivanandham & Gajanand, (2020). Even predictions for platooning made by truck manufacturers have already panned out as overly optimistic (e.g., Ahola Transport, 2018, p. 5; Gilroy, 2017). Hence, it stands to reason that the complexity of challenges associated with truck platooning have likely led to forecasts of its deployment failing to come true.

In 2023, the NPRA invited the broader transportation community in Norway to participate in the establishment of a national strategy for automated road transport. It aimed to coordinate and formalize ongoing initiatives across industry and public entities. The preliminary report was made public in February 2024. It cites three projections for truck platooning (Norwegian Public Roads Administration, 2024, p. 40). In the 2030s, truck platooning is believed to be piloted. In 2050, subject to two levels of technology optimism, it is believed that either 10% of trucks will partake in platooning at SAE level 5 on national roads, or that 90% of trucks will do so. Stated otherwise, the opportunity space regarding the deployment for truck platooning is highly uncertain. Hence, more research is needed to study the effects of truck platooning in jurisdictions where it has yet to be tested, and to tackle barriers to its deployment. Such knowledge may provide guidance for future transportation policy and research activities.

The following subchapter introduces important enabling technologies which underpin truck platooning and automated driving systems at higher SAE levels.

2.1.5 Enabling Technology

This subchapter discusses the technological differences between truck platooning and free-agent automation, before introducing the concept of platoon stability. A succinct overview is also provided of the most relevant sensors and technologies which underpin truck platooning and automated driving, as the case studies encountered, discussed, and made direct use of them.

Truck Platooning versus Free-Agent Automation

Systems for platooning are generally simpler than driving automation systems which may eventually enable higher-level automated driving for free-agent vehicles. Automated driving systems at higher SAE levels must accomplish the tasks of *localization*, *perception*, *planning* and *control* (C. W. Lee et al., 2020; Pendleton et al., 2017). Truck platoons, however, can rely on the driver(s) for many of these tasks. Assuming the following trucks are equipped at SAE level 1, the platooning system only needs to account for limited parts of the control task, to maintain appropriate distance to the preceding truck. The task of perception could also be assisted or partly replaced by wireless transmission of driving commands between the trucks

(Mascalchi & Willemsen, 2020). Systems used by platoon followers at SAE levels 2 and 3 may also need perception systems to detect road markings, in order to accomplish lateral steering control. In any case, the presence of a lead driver removes the need for the localization and planning tasks, the automation of which is fraught with technical difficulty.

Platoon Stability

While truck platooning removes some difficult tasks associated with automated vehicles at higher automation levels, the arrangement of trucks in close proximity introduces new technical challenges. Without wireless communication of driving commands, truck platoons are subject to latency in various sensors and technological components. Since the detection of the preceding truck involves latency, time lag may propagate and intensify rearwards in the platoon, disrupting its so-called *string stability* (Lu & Shladover, 2014). Poor string stability refers to the introduction of errors or disturbances in the system, causing the distance and hence also the spacing between the trucks to differ from intended values (Gehring & Fritz, 1997). Consequently, ACC-based truck platoons are destined to operate at relatively large distances, creating temporal buffers to account for latency. Nevertheless, the latency of ACC-based systems typically results in reaction times which are shorter than those for human drivers. Hence, even ACC-based truck platoons may have trucks which are spaced closer together than what they would be during manual driving.

Vehicle-to-Vehicle communication can mitigate such latency. Specifically, platooning trucks may receive driving commands which are wirelessly transmitted from the lead truck, enabling a concept known as Cooperative Adaptive Cruise Control (CACC), which facilitates more harmonious and coordinated operation (P. Singh et al., 2018; S. Yang et al., 2022). When equipped with such systems, following distances may be reduced significantly, e.g., to 5-10 meters (Tsugawa et al., 2011), or below 0.5 seconds (Nowakowski et al., 2015, p. iii). For instance, the aforementioned Swedish experiments used CACC (Alam et al., 2015). **Figure 2** illustrates the relative following distances used during manual driving, alongside ACC-based and CACC-based truck platooning, respectively.

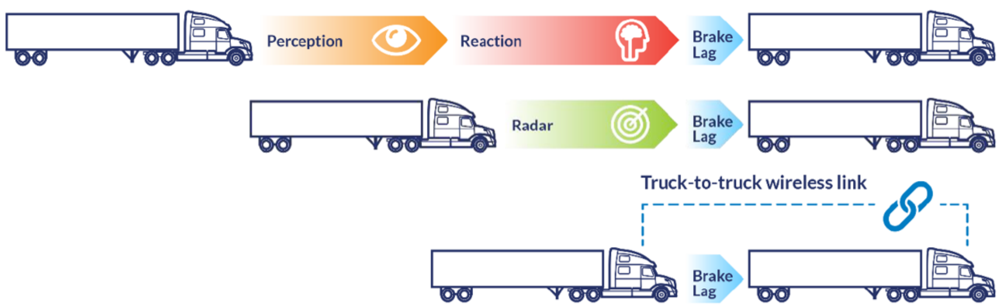

Figure 2: Connectivity and following distances, adapted from Peloton Technology, (n.d.).

Key Technologies

Driving automation systems which enable truck platooning and higher-level automation may use technologies such as *cameras (i)*, *radars (ii)* and *lidars (iii)*, alongside *Global Navigation Satellite System (GNSS) positioning (iv)* and *High-Definition (HD) Maps (v)*. These technologies were encountered in the case studies and are thus briefly introduced here.

Camera

Cameras are cheap and reliable sensors which normally capture the same wavelengths as the human eye (Hakobyan & Yang, 2019; Seitz, 1999). Their high resolution results in large data volumes (Rosique et al., 2019) and hence require significant processing power to extract semantic information. Cameras are also limited by their viewing angle, and they are affected by rain, snow, fog and light variations (Zhu et al., 2012). Moreover, their night-time detection distance is subject to the ability of the headlights to illuminate the surroundings (OECD Publishing, 2023). Camera inputs are often combined with radar and lidar to increase robustness (Murad et al., 2013; Rosique et al., 2019).

Radar

Radio detection and ranging (radar) sensors (Zekavat et al., 2021) transmit radio signals and evaluate their reflections from surrounding objects (Hakobyan & Yang, 2019). Radars work irrespective of ambient light, and can estimate distance to and velocity of moving objects (L. Wang et al., 2021). Generally, radars are reliable in adverse weather such as snow, rain and fog (Bilik et al., 2019; Hakobyan & Yang, 2019), and they produce data at more manageable quantities, and which are simpler for computers to interpret. Radars are susceptible to clutter, meaning unwanted or reflected signals caused by roadside elements such as guardrails, tunnels and walls (Shnidman, 2005).

Lidar

Light detection and ranging (lidar) sensors (Gao et al., 2018) share many characteristics with radars, using light instead of radio waves. Compared to radar sensors, lidars may collect more complex three-dimensional reconstructions of the surrounding environment, referred to as point clouds (Rózsa & Szirányi, 2018). Lidar range is reduced in snowy, rainy, and foggy weather as the refractive index of the air is changed (Yoneda et al., 2019). Lidars are relatively costly in comparison to other sensing systems (Rummelhard et al., 2017).

Global Navigation Satellite System (GNSS) Positioning

GNSS often provides driving automation systems with vehicle location (Joubert et al., 2020). It consists of the space segment (satellites), the control segment (ground stations) and the user segment (receivers) (Rahiman & Zainal, 2013; Zogg, 2009, p. 43). Using the travel time of radio waves transmitted at fixed intervals from satellites with known position, GNSS receivers calculate position and time, from which their speed and travel direction can be derived. Although most GNSS receivers function with just 5 satellites in their field-of-view, most users in the near future will have at least 25 satellites visible at their disposal (Joubert et al., 2020).

Using real-time kinematic (RTK) corrections, GNSS can provide sub-0.35-meter accuracy with 95% reliability (Joubert et al., 2020). The Norwegian Mapping Authority provides such corrections through the centimeter positioning (CPOS) service (Bitney, 2021). CPOS provides corrections over internet or cellular connection, based on the known positions of a network of base stations located throughout the country. This allows receivers to accurately calculate their position (Norwegian Mapping Authority, 2021).

Without RTK corrections, GNSS normally has deviations of up to 5 meters (Strijbosch, 2018). In addition to being dependent on the number of available satellites, GNSS systems are affected by errors in satellite orbits, clock errors, and ionospheric disturbances (Rahiman & Zainal, 2013; Zogg, 2009, pp. 101–102). The surroundings of the receiver can also cause issues. For instance, tunnels cause GNSS-denied areas, and trees, buildings and traffic lights may attenuate, scatter and block GNSS-signals for receivers which happen to be located close by (Humphreys et al., 2020; Joubert et al., 2020). To overcome these challenges, sensor fusion is increasingly used to integrate GNSS with in-vehicle sensor data (S. Liu et al., 2019). This data may also be verified against high-definition (HD) maps.

High-Definition (HD) Maps

HD-maps are high-accuracy digital maps which describe the road, including lane geometry, road markings, traffic signs and other properties of relevance for automated vehicles. Such maps are purpose-built for machine readability and data processing (Strijbosch, 2018), and may be useful since GNSS and sensor-based perception systems may not provide sufficient accuracy and context for automated driving (Jo et al., 2018; S. Liu et al., 2019; Strijbosch, 2018). For example, an in-vehicle camera might detect a speed limit sign belonging to an adjacent road. In such situations, HD maps may provide useful context, enabling automated driving systems to understand whether or not the perceived characteristics are applicable (Strijbosch, 2018; Urmson et al., 2008).

HD maps may facilitate longer planning horizons than those which are available for purely sensor-based perception systems, which are limited by their sensor ranges (Strijbosch, 2018). HD maps may also make automated driving systems less susceptible to bad weather. The need for updates is regarded as a major downside of HD maps, and some developers partner with vehicle manufacturers to access sensor data for updates (Jo et al., 2018; Strijbosch, 2018).

2.2 Norwegian Conditions

This subchapter introduces the relevant characteristics which comprise the backdrop for exploring truck platooning in Norway. It first concentrates on the road freight sector, before providing an overview of the Norwegian road network.

2.2.1 Norwegian Road Freight

This section key attributes of Norway and the Norwegian industrial structure, before focusing explicitly on the Norwegian road freight sector. These two former aspects are included as they justify many of the features of this sector.

The Basics

Road freight refers to the transport of goods over long distances, mostly using road tractors with semi-trailers (European Commission, 2021). Commonly referred to as *trucking*, road freight is widely considered the backbone of modern economies, e.g., Calatayud et al., (2022) and Desrosier et al., (2022), as it is indispensable for keeping supply chains operational. The two most central actors are *carriers* and *shippers*. Carriers are freight companies which own trucks and supply transportation services. Shippers enter into agreements with carriers to move goods between production facilities, freight terminals and marketplaces (Daskin, 1985).

Population and Geography

Demand for road freight is positively correlated with population (Alina et al., 2020). Compared to other European nations, e.g., Germany, with 84.6 million inhabitants (Statistisches Bundesamt, 2024), Norway has a small population of only 5.5 million inhabitants (Statistics Norway, 2023c). Hence, truck platooning in Norway may be limited by its low overall freight demand.

Moreover, the geographic location of Norway atop the Scandinavian peninsula may itself pose a barrier to truck platooning. Specifically, the nation does not serve as a thoroughfare for road freight headed elsewhere, resulting in low overall volumes of trucks. This contrasts nations located more centrally on the European continent, which may benefit more from through-traffic serving as potential partners for platooning. For instance, countries such as Germany, Spain, and France, which both have larger populations and are more centrally located, face an order of magnitude more road freight annually on their respective territories than what Norway does, measured in ton-kilometers (UNECE, 2022). Normalized for population, however, Norwegian roads are in fact subject to more road freight per capita than what is the case for roads in the aforementioned countries. This characteristic is elaborated further in the following sections. While relative volumes of road freight may be high, overall volumes of trucks are arguably more important in determining the viability for platooning. Furthermore, there may also be other factors which influence efficacy of truck platooning in Norway.

Industrial Structure

Norway is a small, open economy that relies on and derives its international competitiveness from trade (Norwegian Ministry of Transport, 2021). The nation is rich in natural resources, such as forests, fishing, minerals, and hydrocarbons. The Norwegian industrial structure is deeply tied to its geography and is part of why the trucking industry faces difficult conditions. Traditionally, heavy industry was located in rural, mountainous areas, due to cheap and immediate availability of hydroelectric power (Bolweg, 2012, pp. 1–2). While high-voltage lines now allow for power transmission over longer distances, many such industrial sites remain operational, providing livelihoods for thriving communities. Over the last 30 years, the fish farming industry has revitalized many coastal districts, and the slaughterhouses and most feed producers are located in coastal areas (Hanssen et al., 2014). Further, the petrochemical industry is also mostly situated in coastal regions, as subsea pipelines from the Norwegian continental shelf emerge onshore in such areas for refining (Norwegian Petroleum Directorate, 2022), and also since ship-based supply operations originate there.

Prevalence and Projections

The aforementioned industries generate large freight volumes, and hence, many Norwegian road freight shipments start or end at facilities located along rural and coastal roads. The scattered industrial structure of the nation, combined with a growing economy, have led to substantial road freight in Norway (Langeland & Phillips, 2016, p. i). Consequently, Norwegian industry has come to depend on the ubiquity, flexibility and speed of road freight (Skaar, 2015, p. 4), providing shippers with door-to-door access to marketplaces.

In fact, freight volumes on Norwegian roads have increased by 150% over the past 30 years (Madslien et al., 2023, p. vi), and the increase is expected to continue. Forecasts suggest a

55% increase over the 40-year period between 2020 and 2060 (Madslien et al., 2023, p. v), and recent revisions of this forecast, based on technological and societal trends, suggest that this growth rate is off to downside by between 1-13% (Handberg et al., 2024, p. 3). Currently, 53% of Norwegian mainland freight transport, measured in metric ton-kilometers, travels by road (Statistics Norway, 2023a). This is materially higher than the EU average of 25% (European Commission, 2023), underlining the significance of road freight in Norway (Langeland & Phillips, 2016, p. iii). National policy documents also acknowledge its importance (Skaar, 2015, p. 4; Vartdal et al., 2020, p. 19). However, this dependence on road freight comes with a cost.

Externalities

Road freight in Norway is a source of negative externalities, some of which truck platooning may address. Specifically, trucking causes a disproportional share of greenhouse gas emissions. Despite passenger vehicles and vans in Norway outnumbering trucks nearly 50-to-1 (Statistics Norway, 2023b), trucks cause more than 30% of road traffic emissions (Miljøstatus, 2023). Having said that, emissions from road freight have essentially flattened over the past decade, despite increased road freight activity. This promising trend has been attributed mostly to biofuels and more efficient engines (Thompson et al., 2022, pp. 32–35).

Another key externality relates to traffic safety. Specifically, the involvement of trucks in traffic accidents typically causes large differences in mass and hence energy between the vehicles involved (Norwegian Public Roads Administration, 2023d, p. 30). Approximately a decade ago, trucks were involved in every third traffic death in Norway (Langeland & Phillips, 2016, p. i), but the figure seems to be improving, and in 2022, trucks were involved in 24% of traffic deaths, totaling approximately 25 in number (Norwegian Public Roads Administration, 2023d, p. 15). In fact, the risk of being injured or dying in a traffic accident involving a truck dropped by 73% and 61%, respectively, between the years 2007 and 2020 (Nævestad et al., 2022, p. i). For reference, accidents involving trucks mostly take place on low-standard roads in Western, Central and Northern Norway (Nævestad et al., 2022, p. i). Hence, It should be studied whether truck platooning can aid in reducing the negative impacts from the trucking industry regarding emission and traffic safety in Norway, especially on such low-standard roads.

Challenges and Competition

Carriers in Norway face difficult operational conditions. In addition to fuel, maintenance, and asset depreciation, Norwegian labor costs are high, such that the cost index for road freight has significantly outpaced the consumer price index for the past few years (Norwegian Truck Owners Association, 2023, p. 6). Prices have not increased correspondingly, putting the operating margins of carriers under pressure (Norwegian Truck Owners Association, 2023, pp. 28–29). Furthermore, Norway, along with other Western countries, have strict hours-of-service regulations to safeguard the working conditions of drivers (e.g., Norwegian Public Roads Administration, 2021a; Siren, 2021, p. 14). Somewhat simplified, the regulations allow drivers to drive for two 4.5-hour periods per day, separated by a 45-minute break. Further, 11 hours per day are regulated as overnight rest (Norwegian Public Roads Administration, 2021c; Stehbeck, 2019), during which the truck must be stationary. While driving regulations are underpinned by good intentions, drivers have to juggle them alongside many other deadlines, such as departure times for ferries, service hours of border crossings, and delivery timelines at goods terminals. In sum, truck drivers are placed under significant pressure (Clouse & Gupta, 1990; Miao et al., 2014). Traditionally, the trucking industry struggles with a poor public image, alongside other systemic issues, such as poor wages and long hours away from home (Chandiran et al., 2023). As a result, the industry faces low recruitment and an ageing workforce (Liachovičius & Skrickij, 2020; Tsugawa et al., 2016), all the while freight demand is growing. The Norwegian Truck Owners Association, through which 3200 Norwegian carriers are organized, estimates that 2500 new drivers are needed every year until 2030 (Norwegian Truck Owners Association, 2023, p. 14) for its members to avoid ceding business to overseas competitors. Platooning may address these issues by alleviating drivers of burdensome tasks, making the profession more appealing.

The road freight industry is also highly fragmented. In Norway, 42% of carriers are owner-operators, meaning that the truck driver runs his or her own small-scale business operation using only one truck. Nearly half of all carriers (48%) operate 2 to 10 trucks, and only the remaining 10% operate more than 10 trucks (Norwegian Truck Owners Association, 2020). Fragmentation makes the industry competitive, which erodes margins for individual carriers. The operating margin for the Norwegian trucking industry has fluctuated around 3-4.5% over recent years (Norwegian Truck Owners Association, 2023, p. 34). This is significantly below other businesses on the Norwegian mainland (Eide et al., 2019), which had, on average, 83% higher operating margins (Norwegian Truck Owners Association, 2023, p. 34). Fragmentation may hinder truck platooning, as it necessitates carriers to cooperate to achieve sufficient truck volumes. Carriers may also not be sufficiently capitalized to adopt new technology. Conversely, fragmentation may spur adoption among carriers seeking to gain a competitive advantage.

Political Objectives

The rise of road freight in Norway has come at the expense of other freight modalities. While policymakers have long aspired to transfer freight volumes away from road, toward rail and sea, proportions are nearly unchanged since the 1970s. This is attributed to the different modes not competing efficiently for the same freight, limiting the transfer potential (Norwegian Ministry of Transport, 2021).

The National Transport Plan, which is published every four years, outlines the overarching policy measures for the Norwegian transport sector. Previous versions of the plan outlined ambitions to transfer 30% of goods which travel 300 kilometers or more from road to sea and rail by 2030 (Norwegian Ministry of Transport, 2021) , despite forecasts that modal proportions were expected to stay where they are (Norwegian Truck Owners Association, 2023, p. 62; Vartdal et al., 2020, p. 14). In fact, 65% of the goods which is transported between east and west of the country, which constitute the main population centers, is deemed unfit for transfer. The expansive terminal structure which has emerged in the greater capital district is listed as a key culprit, as it favors road freight from the European continent (Sundfjord et al., 2018), as opposed to sea or rail. While goods transfer objective has been a staple for many decades, the current National Transport Plan, published in March 2024,has now abandoned it (Norwegian Ministry of Transport, 2024, p. 50), citing similar sources to those mentioned here.

The 2021 National Transport Plan outlined a strategy to increase the efficiency of road freight using longer and heavier European Modular System (EMS) truck trains on larger parts of the road network (Norwegian Ministry of Transport, 2021, p. 117). This reduces the number of trucks and drivers needed to move the same volumes (Vartdal et al., 2020, p. 23). While permitted road sections are gradually increasing, their extent is limited (Dysvik et al., 2020, p. 24), which limits the network effects needed to make operation of such trucks practical and cost-effective for carriers. Perhaps to this effect, the 2024 Transport Plan does not strengthen the objectives for deploying EMS truck trains. Instead, it commissions government agencies to develop knowledge about the climate impacts from freight operations (Norwegian Ministry of Transport, 2024, p. 113). The plan includes measures aiming to expedite the deployment of chargers for electric trucks, and to construct new rest stops to benefit the trucking industry (Norwegian Ministry of Transport, 2024, p. 82). Furthermore, the strategy acknowledges automation as a key trend for road transport (Norwegian Ministry of Transport, 2024, p. 113), but strategies for automating road freight are absent. This may suggest that policymakers are skeptical of the readiness of automated road freight systems, indicating that more research is needed.

In short, road freight is important for Norway. The scattered industrial structure of the nation, alongside the fragmentation of the Norwegian road freight industry, are important attributes. While road freight causes many negative externalities, trends point towards its continued importance in the future. It should be explored whether truck platooning and automated driving can provide a solution.

2.2.2 Norwegian Roads

This section provides an overview of the Norwegian road network, including its ownership structure, its quality and standard, alongside unique topographical traits which have shaped it. This is useful for understanding the viability of platooning and automated trucks in Norway.

Overview and Ownership

The Norwegian public road network comprises 98,000 kilometers of roadways, classified into national (11%), county (46%), and municipal roads (43%) (Norwegian Road Federation, n.d.). Although national roads are the smallest category, they support 52% of all vehicle-kilometers travelled in Norway (Dysvik et al., 2020, p. 9). Excluding a few hundred kilometers of roads which are operated by an independent, state-owned entity (Nye Veier, n.d.), the NPRA operates the national road network (Fagerholt et al., 2023). County administrations, of which there are currently 15 (Norwegian Government, 2022), manage county roads. Finally, municipal roads are operated by 357 municipalities (Bolstad, 2024; Norwegian Public Roads Administration, 2021b).

National roads, shown in **Figure 3**, link the country together and connects it with its immediate neighbors, namely Sweden, Finland, and Russia. County and municipal roads (not shown) have a mixed transport and access function, connecting settlements and local industry.

While the NPRA sets central guidelines to ensure uniform design and safe operation of the public road network, many entities are involved in its governance. This is important in the context of truck platooning and automated vehicles in general, as uniformity of roadways and traffic control devices is posited to be a key attribute for widespread adoption automation (Handberg et al., 2024, p. 50; Tengilimoglu et al., 2023). Since many road freight shipments traverse roads which are operated by different entities, exploring the viability of trucking automation systems constitutes a collective effort.

Figure 3: The national transport network (Norwegian Ministry of Transport, 2009).

State of the Roads

The Norwegian road network is mostly comprised of two-way, two-lane roads. These are roadways with one driving lane in each direction, and no physical division between the travel lanes (Langeland & Phillips, 2016, p. 44). Many road sections are narrow and have difficult alignment (Dysvik et al., 2020, pp. 27–33), referring to the combination of horizontal and vertical road design elements (Norwegian Public Roads Administration, 2019b). Sharp horizontal curves and steep vertical gradients slow down trucks to a disproportionate extent, considering that trucks can weigh upwards of 50 metric tons (Høye & Elvik, 2011), which is up to 14 times more than the permissible mass of passenger vehicles. While grades exceeding 7% are characterized as steep for all vehicle types, grades upwards of 4% may be difficult for trucks, especially during slippery winter conditions (Dysvik et al., 2020, pp. 29–30). Many Norwegian freight routes are also characterized by aspects such as direct-access driveways, adjacent settlements, and roadside terrain which limit sight distances. In fact, 8 in 10 road deaths in Norway involving trucks are head-on collisions and run-off-road accidents, and nearly half of these occur in horizontal curves. Lane widths at approximately half of the accident sites were too narrow for two trucks to be able to pass one another. Conditions were slippery or wet for more than half of these collision types (Langeland & Phillips, 2016, p. iii).

Horizontal and vertical curvature, road width and roughness were used in Dysvik et al., (2020) to assess the technical road quality of the Norwegian road network. Respective threshold values for each road category from an earlier mapping were reused (Norddal, 2016), based on the ability of the road to facilitate appropriate vehicle speeds while maintaining traffic safety. Tight horizontal curves are denoted by small radii, steep grades are denoted by large gradients, and narrow road segments have small widths. Hence, lower-bound thresholds were established for horizontal curvature and road widths, while upper-bound thresholds were used for analyzing vertical gradients. Averaged across all road types, 20% of Norwegian roads fall below the threshold values for horizontal curvature, 7% have grades that exceed the thresholds, and 57% of the road network has insufficient width. Lastly, 42% of the roadways are rough and uneven. The western part of the country fares particularly poorly in all metrics, despite being a key producer of export goods (Nyhus, 2023). Norwegian roads also make sparse use of medians and rumble strips, and have the lowest general speed limits in Europe (David, 2022; Dysvik et al., 2020), at 80 km/h (Norwegian Public Roads Administration, n.d.-a). In fact, despite the average speed limit on the main road network is 80 km/h, the average driving speed is 73 km/h, i.e., an 8% deviation to the downside (Dysvik et al., 2020, p. 41). Driving speeds in Norway are significantly below those in comparable European countries (Dysvik & Bjørkås, 2021, p. 8). Norwegian roads are consistently ranked among the safest in the world (OECD Data, n.d.).

Topographical Characteristics

Many of the aforementioned aspects related to the state of Norwegian roads are rooted in local topographical characteristics. The topography of Norway is characterized by deep fjords and valleys, tall mountains, and highlands, necessitating tunnels and ferry connections. In fact, Norway has the second longest coastline of any country in the world (Norwegian Government, 2015). Hence, ferries constitute an important part of the road network, and there are approximately 130 ferry connections nationwide (Solvoll, 2023). Moreover, Norway has in excess of 1,200 road tunnels (Nævestad & Blom, 2023), punching far above its weight on the international stage. This is a challenge for vehicle automation, as tunnels cause GNSS-denied areas, making positioning difficult (Onyekpe et al., 2021). Furthermore, 41 of these are subsea tunnels, with grades often exceeding 7% (Nævestad & Blom, 2023), placing high demands on brakes and drivetrains of the trucks traversing them. Finally, large parts of the nation is prone to difficult winter conditions, landslides and flooding, posing risks to the safe and reliable movement of people and goods (Norwegian Road Federation, n.d.).

Roads in Norway have traditionally been designed to appear as natural parts of the landscape and conform to its features (Norwegian Public Roads Administration, 2019a). This tradition is rooted in topographical conditions, high construction costs, and an appreciation of the natural environment. Hence, two-way, two-lane roads have often been preferred, and thus comprises most of the road network. Still, since truck platooning thus far has mostly been studied on motorways, the following section introduces the Norwegian motorway network.

Motorways

The Norwegian motorway network is limited, comprising only about 1,000 road-kilometers, or 1.1% of the total public road network. This is low compared to other European nations (Dysvik & Bjørkås, 2021, p. 16). In terms of motorway density, measured as the number of road-kilometers per 1,000 square kilometers of surface area, most of Norway has less than five. The capital area is a notable exception, with a motorway density of 15-30 road-km per 1,000 sq. km. In contrast, Denmark and Southern Sweden are better covered (30-50), while most of Finland and Northern Sweden match Norway well (European Commission, 2020). **Figure 4** illustrates the Norwegian motorway network as of 2019, including planned stretches which are yet to be built. Juxtaposed with the national road network in **Figure 3**, it becomes clear that motorways comprise a minority of Norwegian roads.

Political efforts in Norway to expand the motorway network have been shifting over time. Lately, motorway construction projects in Norway have been heavily scrutinized for environmental impacts, and their underlying need for getting built is often questioned (Sandberg, 2023). In spring 2024, a report was written for the NPRA which suggests that future infrastructure management will be most cost-effective if current roads are optimized for uptime and reliability, and if roads are made to facilitate the use of automated vehicles. The report outlines that doing so may entail costs for new physical infrastructure (Handberg et al., 2024, p. ii). However, it makes no mention of whether this may require or be aided by further motorway construction.

In summary, Norwegian roads are mostly two-way, two-lane roads, and this is likely to remain the case. This may make it difficult to operate automated vehicles and truck platoons in Norway. It may also reduce the usefulness of such vehicles (Turri et al., 2017), compared to countries unencumbered by poor road standard, weather-related challenges, and scattered operational responsibility for public roads.

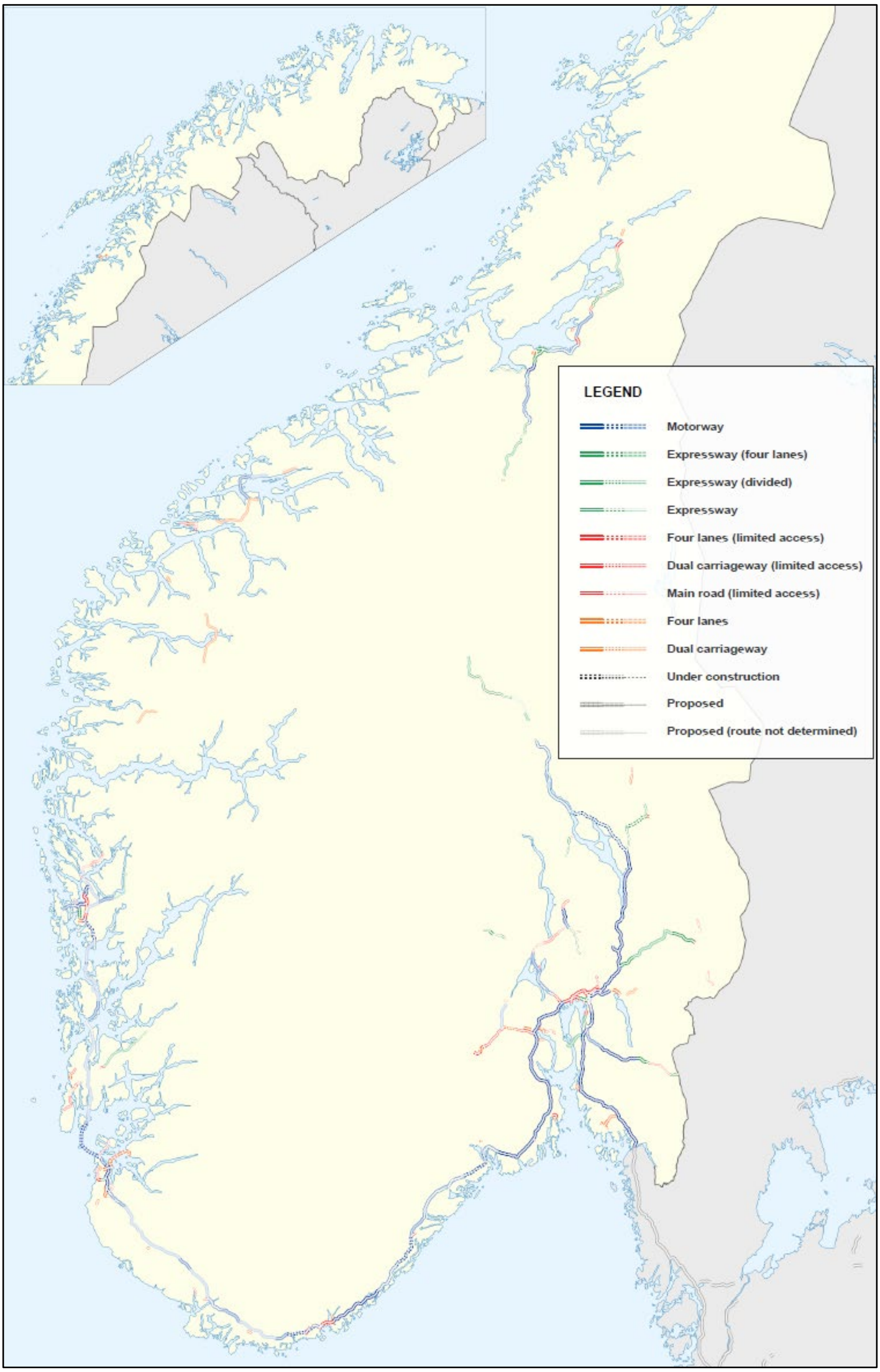

Figure 4: Motorway network in Norway. Modified from Wikimedia Commons, (2019).

3 Methodology

This chapter showcases the research design used in the three case studies. The first subchapter provides an overview and describes the interrelationship between the case studies, and it describes their areas of focus. The following subchapters detail the specific methods applied in each case study. **Table 5** provides a summary.

3.1 Overview

This thesis was in large part motivated by a demonstration of truck platooning which was conducted in 2018, constituting the first of its kind in Norway (Norwegian Public Roads Administration, 2018a, 2018b). The demonstration was mostly intended to generate public interest during the opening of a testbed for ITS technologies in Northern Norway (Haugland, 2020). Hence, it did not have an academic focus, and it did not include any data collection efforts. However, it sparked the curiosity of the NPRA, and it revealed knowledge gaps related to the ability of Norwegian roads to accommodate truck platoons. It also made it clear that the potential benefits and barriers of truck platooning in Norway are not well understood.

Motivated by the aforementioned demonstration, the current work set out to explore whether practitioners believed truck platooning would be feasible and worthwhile. Real-world deployment of truck platooning has been found to hinge upon relevant stakeholders in the transport sector being aligned (Bakermans, 2016). Several country-specific whitepapers exist regarding truck platooning, e.g., from the United States (Noruzoliaee et al., 2021), the Netherlands (Bakermans, 2016; Janssen et al., 2015; D. Yang et al., 2019), Sweden (Axelsson et al., 2020; Kammer, 2013) and Australia (World Maritime University, 2019). However, the specific attributes of the Norwegian context makes it such that international studies are of limited relevance. Hence, the Stakeholder Study provided a local perspective on the applicability of truck platooning. Interviews were conducted with local experts and practitioners, to explore perceived opportunities and barriers associated with truck platooning in Norway. As also found by other researchers, e.g., Axelsson et al., (2020), unlocking benefits from truck platooning was found to involve challenges across the four themes which were introduced in subchapter 1.2, namely *conventional infrastructure* (i), *organization* (ii), *enabling technology* (iii), and *economics* (iv).

A Field Study of truck platooning was also undertaken to address operational knowledge gaps which could not be identified from interviews with stakeholders. Drawing inspiration from the aforementioned 2018 demonstration, a three-truck platoon operating at SAE level 1 was tested on a difficult rural road. This distinguishes the Field Study from most other field trials, typically having taken place on flat, high-standard roads (Turri et al., 2017). A field study was chosen, as opposed to other research methods, as it would enable rapid learnings related to the technology in an applied setting (Asare et al., 2020). The platoon and its participants were monitored using multiple cameras and sensors. This provided detailed knowledge into platoon behavior in the different driving situations which were encountered.

The Field Study was undertaken with trucks operating at the low end of the automation taxonomy. Hence, to be able to conjecture with more validity about future developments in automated trucking, it would also be useful to study applications at higher SAE levels than are currently available on open roads in Norway. Enclosed industrial areas were quickly identified as promising candidates for such an endeavor, considering that automation has already been deployed in various confined areas for logistics and freight, such as ports, warehouses and factories (Bhoopalam et al., 2018; Discovery UK, 2020; C.-I. Liu et al., 2004). Presently, only two Norwegian industrial use-cases exist which involve automated trucks as part of real-life commercial operations, at higher levels of the SAE taxonomy. Project managers from these use-cases were interviewed in the Industrial Study. The aim of the study was to assess how challenges related to infrastructure, organization and technology were overcome, and to explore the economic driving forces behind such projects. The study was motivated by the fact that such projects may serve as catalysts for downstream developments in the public roads sector. Specifically, they may inform future research efforts and provide suggestions to promote on-road automation.

Table 5: Overview of methods.

Case study	**Data**	**Main Method**	**Main Analytical Approach**	**Objective**
Stakeholder study	Traffic and ferry data, Interview transcripts	Semi-structured interviews	Qualitative, Exploratory	Obtain an overview of stakeholder opinions towards truck platooning
Field study	Radar data, Video footage	Field trial	Mixed methods	Assess distances between platooning trucks
	Videos, Interviews, Conversations, Radar data, Fleet management data			Explore the operation of a truck platoon on difficult rural roads
Industrial study	Interview transcripts	Semi-structured interviews	Qualitative, Exploratory	Study challenges of trucking automation in enclosed areas

Investigating the potential for truck platooning in Norway required exploring both technical and social scientific perspectives. Collectively, the three case studies were designed to facilitate this breadth in scope. Hence, this work employed the principle of *triangulation*, referring to the use of multiple research approaches to obtain complementary data about the subject, in order to increase the validity, depth and consistency of the results (Bryman, 2004; Wilson, 2014). This thesis mostly employed triangulation of *data* and *methods*. The former refers to the use of different data sources and sampling strategies, and the latter involves the use of different types of data collection efforts. To illustrate the different scopes of the four papers which were introduced in subchapter 1.5.1, **Figure 5** structures them based on their focus. The papers are positioned relatively along a vertical axis spanning the conceptual spectrum from a technical, microscopic, and quantitative perspective at the origin, to a societal, macroscopic, and qualitative perspective at the upper end.

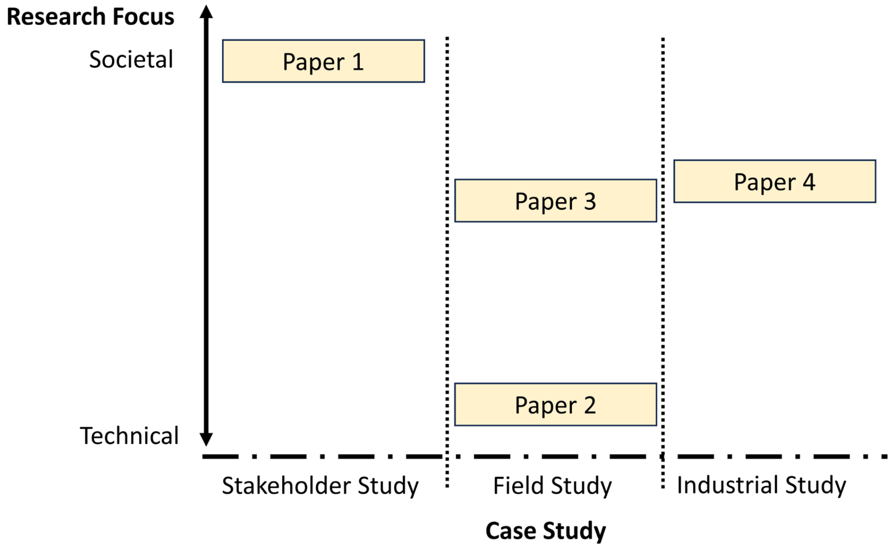

Figure 5: Relative ranking of papers based on research focus.

3.2 Stakeholder Study

The Stakeholder Study investigated the viability of truck platooning in Norway. The following sections describe the interview process, the participants, and the case examples which were included in the interviews. The process for data analysis is also briefly described.

3.2.1 Interviews

Stakeholders are generally defined as groups of individuals who share a common interest in a particular issue (Grimble & Wellard, 1997). For instance, stakeholders can affect the viability of truck platooning by developing new technology, permitting its use, and by providing necessary infrastructure. Carriers and truck drivers must naturally wish to use the technology, and other road users must also approve of it.

Expert and snowball sampling was used to recruit 21 individuals across the road transport sector, based on their knowledge and experience in Norwegian road freight, Norwegian road infrastructure, or driving automation systems. Expert sampling is applicable when investigating new research areas (Etikan et al., 2015). Snowball sampling was also used (e.g., Parker et al., 2019). Specifically, some interviewees suggested other experts or institutions which could constitute relevant and knowledgeable participants, some of which were recruited to take part in the study. The chosen number of interviewees was considered sufficient once incremental interviews provided diminishing returns.

All interviewees were provided with an information letter in advance, and a general interview guide was created to guide the discussions. In this respect, the methodology was similar to that used by Kacperski et al., (2020). Interviews with 90-minute durations were undertaken digitally. These were recorded and transcribed, and all personal details were anonymized. Semi-structured interviews were used since the format frames the discussions well, while allowing for exploring new perspectives brought up by participants (Cohen & Crabtree, 2006).

3.2.2 Participants

Interviewees represented carriers (n = 4), shippers (n = 4), researchers (n = 4), NPRA (n = 3), county administrations (n = 2), interest organizations (n = 2), railway terminal owners (n = 1), and a truck manufacturer (n = 1). The interview with one of the shippers included two participants from the same company. The same was true for one of the carrier interviews. The other interviews were conducted with participants individually. Seven interviewees happened to be former truck drivers. The interviewees often also made remarks from the standpoint of using the road network as conventional road users. The upcoming sections provide more details regarding the different groups of participants.

Academia, Truck Manufacturer, and the Public Sector

Participants from research institutions included economists and experts in road freight and intermodal transport. The interviewee from the truck manufacturer had been involved with developing the adaptive cruise control system used in their most recent truck line-up. The county administrations were interviewed in their role as road owners and operators, and the NPRA was interviewed for its role as road owner, operator, and also as regulator at the national level. The interviewee from the railway terminal represented the largest rail freight terminal in Norway, and the interview explored how truck platooning may augment intermodal rail freight operations.

Carriers

The carriers were of different sizes, and they operated on different routes within Norway. The largest one is a substantial multinational company which organizes freight across all modalities, managing goods terminals in most cities across Norway and Europe. In Norway, it operates more than 850 trucks per day, which drive throughout the nation with over 1,100 drivers. The medium carrier was a large grocery wholesaler which operates more than 600 trucks daily. This carrier ships most of its volume from a central storage facility located in the greater capital area. The smallest carrier operates approximately 25 self-owned trucks, but it also contracts with external drivers, bringing the total to around 100 trucks. Like the medium carrier, this one also supplies grocery chains, its shipments also originating at a central storage facility in the capital district. While the other two carriers operate throughout the country, the shipments of the smaller carrier are mostly delivered in Western and Central Norway.

Shippers

The shippers included a seafood corporation, a furniture manufacturer, and a natural gas distributor. All shippers are among the most prominent companies in Scandinavia in their respective markets. The seafood corporation operates mainly in Western, Central, and Northern Norway. The furniture manufacturer operates both in Western and Eastern Norway, while the natural gas distributor is based far north, above the Arctic circle. Hence, the shippers represented industries located in rural and coastal areas, introducing aspects of rural freight routes, which are likely to have lower truck volumes and road standards. These attributes were believed to complicate the upfront coordination and operation of truck platoons.

Research indicates that shippers generally have low willingness to pay for additional services, such as more environmentally friendly freight options (e.g., Johansen et al., 2018). Moreover, shippers have few commitments to specific carriers, making it difficult for carriers to create lasting competitive advantages (Grønland et al., 2014; Hovi et al., 2014, pp. 16–17). Nevertheless, shippers may set demands when procuring carrier operations. Specifically, they may mandate the use of certain modalities (Skaar, 2015) to comply with climate goals. To this effect, shippers were asked to what extent this could be relevant for truck platooning.

As truck platooning in Norway will likely necessitate some waiting to coordinate, this may affect shipment time and hence influence the efficacy of platooning. The shippers were also thought to have different thresholds for lead time variability. For instance, compared to shipments of non-perishable goods, the value of fresh seafood depends strongly on transit time (Grünfeld et al., 2020). Hence, such shipments may be unfit candidates for truck platooning, with respect to warranting the incurrence of waiting-related costs. Consequently, shippers and carriers received additional questions regarding contractual agreements, goods volumes, and the geographical and temporal reliability of their shipments. Compared to the other shippers, which purchased transportation from carriers, the natural gas distributor served as its own carrier. It hauled liquified gas, often over long distances, for industrial clients.

3.2.3 Case Examples

Five realistic case examples, described in **Table 6**, were presented to interviewees, grounding them in local conditions to contextualize the topic and elicit commentary. The following three paragraphs describe key attributes of the case examples. Platoons consisting of two trucks were used in all examples.

Ferries and Hubs

Ferry terminals are integral constituents of many freight corridors in Norway. While waiting for the ferry to depart, trucks can coordinate to form platoons for the downstream section of the trip that they share after disembarking. Such coordination can occur at zero marginal cost, and the large, paved areas of such terminals may facilitate coordination (Kjær Rasmussen et al., 2017). To elicit feedback to this idea, most case examples involved ferry crossings. Truck volumes were checked for two important ferry connections and were used as input for discussing strategies for coordinating platoons. The idea of waiting for a partner at truck stops was also included (e.g., Engström et al., 2019). For those examples, average waiting times were calculated based on data from nearby vehicle detection loops.

Fuel Savings and Waiting-Related Costs

Assumptions for fuel savings were based on flat 5% reductions per truck, compared to a manually driven baseline estimate. While this would be high for the lead truck, it may be conservative for the following truck, compared to the scientific literature. Hence, it was seen as a simplified way to obtain rough estimates on fuel savings, which could be used to facilitate discussions. The case examples also elicited responses to the idea of calculating an inconvenience cost associated with waiting for a partner to establish a platoon, alongside the effects which such a wait might have on daily available driving time, as well as the possibility for value loss of onboard cargo. Further, drivers may be hardwired to keep moving, making waiting less likely for short trips, as suggested by Axelsson et al., (2020), based on cost-benefit analyses.

Other Ideas

The case examples also speculated on having occupants in following trucks resting. This engaged the interviewees in commentary about whether it would be feasible from a regulatory standpoint, and how it may be compensated. As an extension of this, the case examples illustrated how this may create scheduling flexibility, enabling truck platoons to bypass road closures using alternative routes which may be too long to drive for one driver in solitude. Continuous two-truck platooning, resembling the double-manning concept (Kopfer & Buscher, 2015; Stehbeck, 2019), could enable same-day service between many Norwegian cities for which this is not currently the case. The goods transfer objective, described in subchapter 2.2.1, was still in effect when the Stakeholder Study was undertaken. Therefore, discussions were elicited regarding whether or not such expedited service could inadvertently lead to unintended modal shifts away from rail or sea.

3.2.4 Data Analysis

Interview transcripts comprised 240 pages. Once transcribed, statements were coded in NVivo 12, a software tool for organizing and analyzing qualitative research data. For text, *coding* refers to the labelling of statements, as a first step to uncover underlying themes (Dhakal, 2022). In sum, 31 codes were defined, and 2,600 statements were ascribed to them. **Figure 6** shows the 12 codes with the most references. The five top codes comprised 38% of the data. The codes were aggregated into six themes which were used to structure Paper 1. Statements were condensed when writing, attempting to retain the original meaning of each remark.

Table 6: Overview of case examples used in Stakeholder Study.

Case	From-To	Ferry	Description
1	Stavanger-Haugesund	Mortavika-Arsvågen	High-frequency ferry crossing with enough trucks for platooning Short platooning duration and few savings.
2A	Narvik-Bodø	Kjøpsvik-Drag	Few daily departures, but this groups trucks, making platooning feasible from all departures. Assumes 20% labor savings for the following driver.
2B			Like 2A, but platooning ceases at a hub at Fauske, followed by manual driving to the destination.
2C			Like 2B, but with a 10-minute wait at Fauske, to convene with a new partner.
3	Fauske-Alta	Drag-Kjøpsvik	Shows platooning as an extension of the rail network. Assumes that time spent as follower does not count towards driving time. Drivers switch roles and reach the destination faster by avoiding overnight rest.

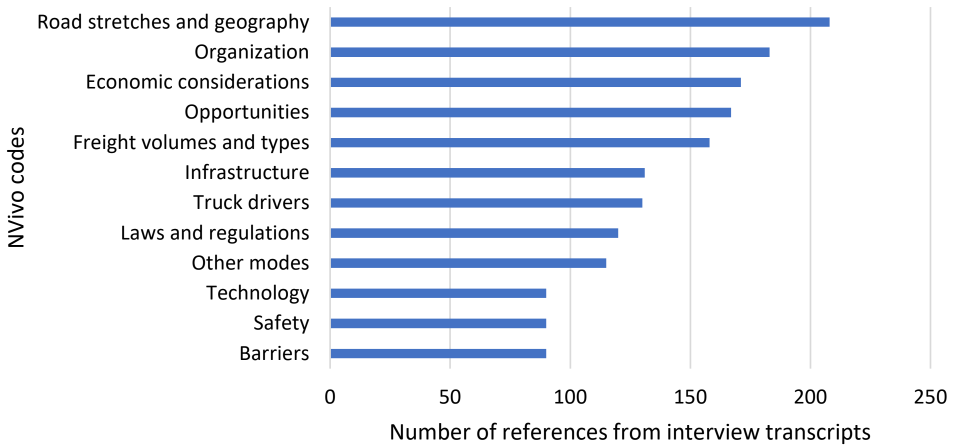

Figure 6: Overview of the 12 codes from the Stakeholder Study with the most references.

In summary, the Stakeholder Study used semi-structured interviews and case examples to elicit viewpoints from practitioners in the transportation ecosystem towards the viability of truck platooning in Norway. The study culminated in Paper 1.

3.3 Field Study

The Field Study tested truck platooning on challenging rural roads. Involving three trucks, platooning was explored without the coordination-related issues which it may entail as part of real-life shipments. Barnard et al., (2016) discussed methodologies for conducting field studies with automated vehicles. Based on their three-part taxonomy, the Field Study may be characterized as a *vehicle-centered test*. The platoon was instrumented to collect both quantitative and qualitative data pertaining to the effects of road standard, traffic, and driver behavior. Hence, the terms *mixed methods* or *multimethod research* (Bryman, 2004) are suitable, denoting the integration of qualitative and quantitative approaches (Tashakkori & Creswell, 2007).

The following subchapters introduce central aspects of the Field Study, including the route, the trucks and platooning systems, the participants, instrumentation, and data analysis methods.

3.3.1 Route

The route for the Field Study is important for Northern Norway, with few alternative bypasses, cold climate and frequently changing weather (Bardal, 2017). Semi-trailer trucks make up a large share of traffic on the route (Hanssen & Solvoll, 2014, pp. 9–10) , making platooning here realistic from a volume perspective. This is supported by calculations from vehicle detection loops at Ulvsvåg, where, from 2020 to 2023, semi-trailers comprised between 8 and 10% of the traffic volume. Most of the route, shown in **Figure 7**, is shared between case examples 2A-2C in the Stakeholder Study. While the route is 380 kilometers long, one section was traversed repeatedly, with altered truck orders. Hence, the driving distance was 420 kilometers. Data from these repeat runs mostly had to be omitted from analyses, due to instrumentation issues, and due to their lack of predictive validity, as they were comparatively short.

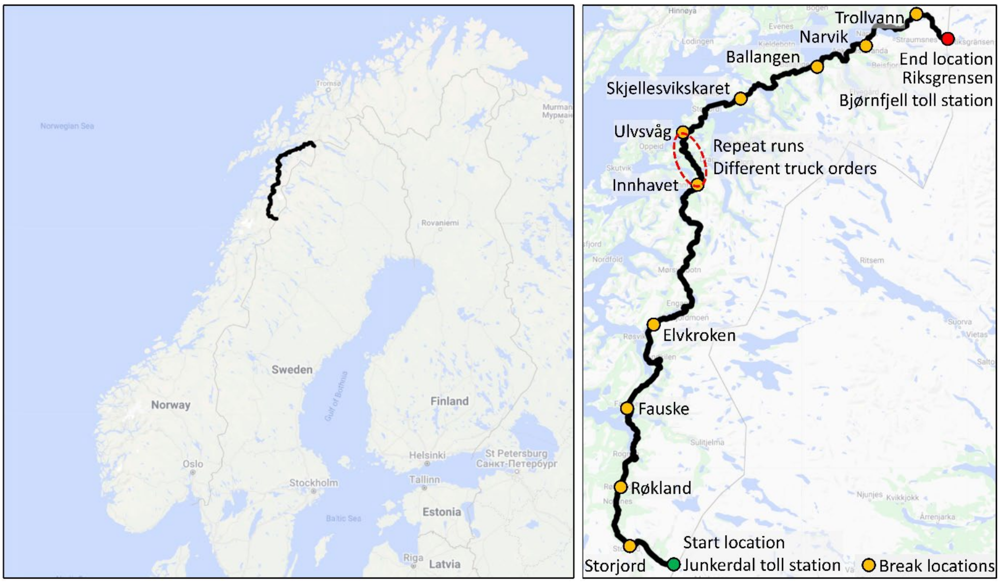

Figure 7: Overview of Field Study route.

The most challenging section of the route lies between Fauske and Innhavet, and consists of 100 kilometers of winding curves, steep grades and narrow tunnels, many of which are in poor condition and do not meet safety standards (Brovold, 2013; Kersting & Hansen, 2022, pp. 17–19; Norwegian Public Roads Administration, 2023b). The stretch is accident-prone and often has to be closed for heavy vehicle recovery in winter, e.g., Bye, (2021). Previous work indicates that vertical grades make it hard for platoons to stay connected (Chen et al., 2018), as spacing errors accumulate over time, making the platoon unstable, eventually requiring intervention by the drivers. The route provides ample opportunity to verify this presumption. Still, limited segments have been modernized, such that the stretch provides large variations for testing.

3.3.2 Trucks

The three trucks which participated in the test are shown in **Figure 8**. In addition to the route having many sections of subpar road standard, weight differences were introduced to further challenge the platoon. These were presumed to destabilize it further, necessitating communication and ACC adjustments to retain connection. Trucks 1 and 2 had a mass of 41 metric tons, whereas truck 3 weighed 27.5 metric tons. Apart from this, the trucks were identical. They were equipped with a prototype ACC-based platooning system (Ahola Transport, 2018), which was jointly developed by the truck manufacturer and the carrier who took part in the study (Scania Group, n.d.).

Figure 8: Truck platoon parked at Junkerdal toll station (Solberg, 2020).

3.3.3 ACC-Based Platooning System

Little information was provided regarding the technical workings of the ACC-based platooning system, presumably due to its developmental and proprietary nature. Other researchers have faced similar problems, e.g., Ulrich et al., (2020). Still, the workings of a commercially available version of the system were described in the driver manual, which confirmed descriptions of the system made by the participants during the Field Study.

Using a fictional speed profile, **Figure 9** illustrates the operation of the ACC system in the Field Study. Specifically, it shows the cut-offs between different regimes for automated longitudinal control for a following truck, assuming the presence of a preceding truck. Drivers were first required to manually accelerate up to at least 15 km/h, upon which conventional ACC became available for them to activate by pressing a button on the steering wheel. Adjacent buttons were used to choose the desired driving speed, and to choose the speed limit for downhill speed control (DSC). The DSC prevented the trucks from exceeding the determined maximum velocity, by automatically engaging braking systems when required (Alam et al., 2015). The following trucks used settings for speed and DSC which slightly exceeded those used by the lead truck, in order to retain platoon connection. This was also the case in the experiments by Alam et al., (2015). In the Field Study, the drivers chose between one out of five available gap sizes, indicated by horizontal bars in the instrument cluster. Two bars were often used. The distance represented by the bars changed dynamically based on vehicle speed, but corresponded to following gaps of 2-3 seconds, at the shortest. The trucks were also equipped with an eco-roll system which determined optimal gears, and which engaged neutral to allow the trucks to coast freely over crest curves (Scania Group, 2018). This eco-system was based on maps of the road geometry for the upcoming three kilometers.

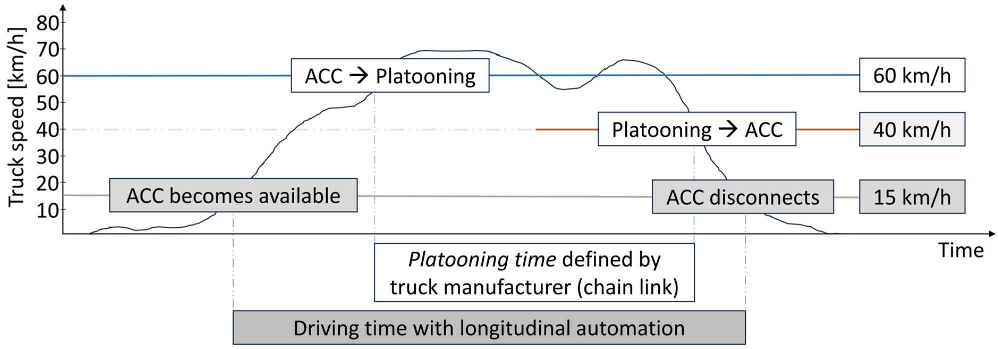

Figure 9: Cut-offs between different longitudinal systems as a function of speed.

Conventional ACC would transition to ACC-based platooning if the truck speed were to exceed 60 km/h, given the presence of another truck preceding it. The preceding truck had to be sufficiently close, such that it would be detected by the integrated camera and radar sensor in the following truck. The gap size of the following truck also had to be defined by the driver as either one or two bars. Once active, ACC-based platooning was illustrated as a *chain link* in the instrument cluster. If the chain link was active and speed dropped below 60 km/h, it remained active until speed dropped below 40 km/h, upon which the system classified the platoon as disconnected, the chain link disappeared, and conventional ACC automatically took over. If speed dropped below 15 km/h, conventional ACC was automatically disconnected. A visual and audible warning signaled that longitudinal control was transferred back to the driver. If the ACC system was activated but no preceding truck was present, conventional ACC remained connected until speed fell below 15 km/h. The trucks had a Lane-Keep Assist (LKA) system which provided limited lateral support, so the drivers steered manually throughout the Field Study.

Figure 10 shows the platoon traversing a bridge at Sørstraumen, while **Figure 11** shows the platoon climbing the Skjellesvikskaret mountain pass. The speed of the platoon in the pictures was 65 km/h and 35 km/h, respectively. In both situations, longitudinal automation was active in the following trucks. While illustrating the Norwegian context, the figures also showcase typical following distances used in the Field Study, when travelling at typical speeds.

3.3.4 Participants

The three drivers did not have experience from driving together, but had previously driven in Norway, and they had used conventional ACC systems before. They were encouraged to use the platooning system, but they were instructed to disable it, if necessary. Each truck had a passenger, acting as an observer. Two of them were managerial employees at the carrier, and one was a doctoral student who had previously been involved in platooning research with the carrier. Before the study, the participants were provided with an information letter, and informed consent for data collection was obtained.

The platoon was accompanied by support vehicles which accommodated the researchers and test organizers. One or two vehicles were often located a kilometer or so ahead of the platoon, while remaining ones were located behind it. All vehicles were equipped with handheld VHF radio transceivers. This allowed drivers and passengers in platooning trucks to communicate, and for the test organizers to coordinate and warn the platoon of potential dangers.

Figure 10: Platoon traversing bridge (Norwegian Public Roads Administration, 2020).

Figure 11: Platoon climbing mountain pass (Norwegian Public Roads Administration, 2020).

3.3.5 Aftermarket Instrumentation

The carrier provided outputs from a fleet management system. This was complemented using aftermarket instrumentation to capture the behavior of the platoon. The data collection efforts were based on best-practices from previous research, e.g., Lu & Shladover, (2014) and Tsugawa, (2013) for using radar sensors to study fuel consumption, and Stapel et al. (2022) for filming drivers. Petroskey et al. (2020) also detailed positive experiences with Racelogic VBOX data loggers and GoPro action cameras for collecting telemetry, meaning data streams such as speed, positioning, and acceleration. The trucks were identically equipped, as summarized in **Table 7**. For safety reasons, all instrumentation had to be mounted inside the trucks. This was advised against in literature, due to degraded operation of GNSS receivers (Petroskey et al., 2020) and radar sensors (Franke et al., 1999). However, it simplified the instrumentation process. The following sections discuss radar sensors and GoPro cameras in more detail, as they together comprised the majority of data collection and analysis efforts.

Radars

Previous research suggests that fuel savings from platooning are greater if distances between the trucks are shorter. Thus, the greater the stability of short inter-vehicle distances over time, the more beneficial platooning will be. The Field Study was expected to expose the platoon to combinations of external traffic, road alignment and truck weight differences which would impact inter-vehicle distances. To quantify the impacts, inter-vehicle distances were collected. While integrated sensors would have been the most ideal source of such data, access to their outputs could not be provided. Hence, aftermarket sensors were used instead (uRAD, 2020). This set-up also provided data from driving periods within tunnels, where GNSS data was unavailable. Paper 2 details the efforts, which are of value for researchers aiming to collect and analyze radar data from similar trials.

Cameras

Cameras are often used to study the behaviors of drivers and vehicles (Dingus et al., 2016; H. Singh & Kathuria, 2021), for traffic safety, road design and ITS research (H. Singh & Kathuria, 2021). Truck platooning and ACC systems have also been studied using videos. For instance, Friedrichs et al. (2016) recorded steering wheel interactions, and in Stapel et al. (2022), driver foot placement was filmed with a camera in the pedal bay. In B. Zhang et al. (2019), videos were coded to study response times for take-over requests from automated to manual driving in a driving simulator. These studies inspired the use of video footage in the Field Study.

Access to the engagement status of the two different longitudinal automation systems described in subchapter 3.3.3, was not available. Hence, SQ11 cameras were used to record symbols in the instrument cluster pertaining to longitudinal automation. Unfortunately, these cameras were hard to operate. Later attempts were made to discern this information from the GoPro cabin cameras. These were mounted rather high up on the driver door, and they were therefore located far away from the instrument cluster. Moreover, sun glare and dark displays made the symbols unintelligible for large portions of the drive. Still, the pedal bay and cabin cameras made it easy to discern *manual* from *automated* longitudinal control, as they showed the periods when the driver chose to activate and deactivate the overall system. The two longitudinal systems, however, could not be distinguished from one another. Hence, data analysis was based on the total *driving time with longitudinal automation*. Since the two systems differ based on the presence of a lead truck, data collection included periods where the trucks were located further apart than is conventional in previous truck platooning research. The dashboard cameras was used to contextualize the driving scene. In total, 80 hours of high-definition video was collected, over the 7.5-hour driving duration.

Table 7: Overview of vehicle-mounted aftermarket instrumentation.

Equipment	Objective	Details
Anteral uRAD radar sensor (uRAD, 2020)	Measure distances to the preceding truck to determine how inter-vehicle distances fluctuated during the drive.	Windshield-mounted Raspberry Pi microprocessor with a radar device attached.
GoPro Hero 9 action camera (GoPro, Inc., n.d.)	Dashboard camera for filming the driving scene.	Mounted as far up as possible in the windshield using a suction mount.
	Cabin camera for filming the hands and steering movements of the driver to capture interventions with the driving automation system, i.e., adjustments to speed or distance settings, or braking using the retarder.	Mounted to the driver door, above the head of the driver.
	Pedal bay camera for filming the right foot, i.e., the pedal movements of the driver, to capture interventions using brake or accelerator pedal.	Mounted to a cupholder on the steering console.
VBOX Sport data logger (Racelogic, 2014)	Collect telemetry.	Data loggers were placed on the dashboard of each truck.
Instrument cluster camera (SQ11) (ChinaTech, 2019)	Small, inexpensive micro-cameras to film platooning system engagement status, as it was visualized through symbols in the instrument cluster.	Mounted to the steering column.

Figure 12 illustrates the aftermarket instrumentation from inside and outside of the trucks. The radar sensor and dashboard camera are shown in dashed lines in the interior photo. These two devices were visible from the outside, where they have been circled using solid lines.

Figure 12: Instrumentation: GoPro (red), SQ11 (green), radar (yellow) and VBOX (blue).

3.3.6 Data Analysis

Since the instrumentation set-up differed from other field tests, data analysis methods mostly had to be devised from the ground up. **Table 8** provides an overview of data analysis efforts, and a note on the degree to which each one was successful. See also Vindenes, (2022) for more details.

As briefly mentioned in subchapter 1.5.1, the main purpose of Paper 2 was to detail the efforts to filter, analyze and contextualize radar data. Therefore, they are not repeated here. However, the framework for video coding has only been partly presented in Papers 2 and 3, such that a full summary is warranted. Afterwards, the methodology for obtaining qualitative data from participants is detailed, followed by a note on the extraction of road alignment information, both of which were useful for Paper 3.

Table 8: Overview of data analysis efforts in the Field Study.

Data Source	Analysis and commentary
Anteral uRAD radar sensor	Filtering and analysis as described in Paper 2. Time-consuming to synchronize, filter and analyze.
VBOX Sport data logger	Visual inspection in QGIS. Data was unfortunately not collected for all three trucks simultaneously. Some areas were without data.
GoPro Hero 9 action cameras	Manual video coding in BORIS. Transcription and thematic coding of conversations during the Field Study.
Fleet Management System	Analysis of driving speed and fuel consumption. GNSS locations were inspected in QGIS and were quite accurate, but their timestamps for logging were occasionally misaligned. Infrequent loggings (0.02 Hz) could not be used to study short-lived events during driving.
Instrument cluster camera (SQ11)	These cameras were clunky and difficult to operate, filmed with poor quality, and only supported 32 GB memory cards, which ran full without notification. Hence, this footage was later discarded.

Video Coding

Once videos had been recorded, points of interest in the videos had to be identified (Valero-Mora et al., 2013). This is referred to as *coding*, meaning the establishment of a timeline of events (Mossi et al., 2014) in order to quantify and study qualitative phenomena. Videos were synchronized and coded in *Behavioral Observation Research Interactive Software* (BORIS) (Friard & Gamba, 2016). BORIS is a free, open-source video coding tool. While originally developed for studying animal behaviors, BORIS has previously been used in traffic engineering research, for instance to study the behavior of pedestrians in relation to automated vehicles (Rasouli et al., 2017).

Driving was divided into segments, based on locations where the cameras and radars were started and stopped. A synchronization method using a cell phone clock ensured that it would be possible to compile radar data and videos from all trucks along a common timeline. The *ethogram* in BORIS was used to define all relevant, codable behaviors. Events can comprise either *point events* or *state events*. *Point events* have no duration, i.e., they are instantaneous, whereas *State events* do have a duration. Specifically, *State events* are defined with a start timestamp and an end timestamp. Examples of point events are button presses and passing vehicles, while tunnel traversals and winter conditions are examples of state events.

Ultimately, 38 codes were created, shown in **Figure 13**. Note that *Radar logging* was the only video code (except for *Break*) which was logged during non-driving periods. This code refers to the activation of the radar script to start logging. It was coded using cabin camera footage, during breaks. Therefore, the cabin camera is listed twice in the figure.

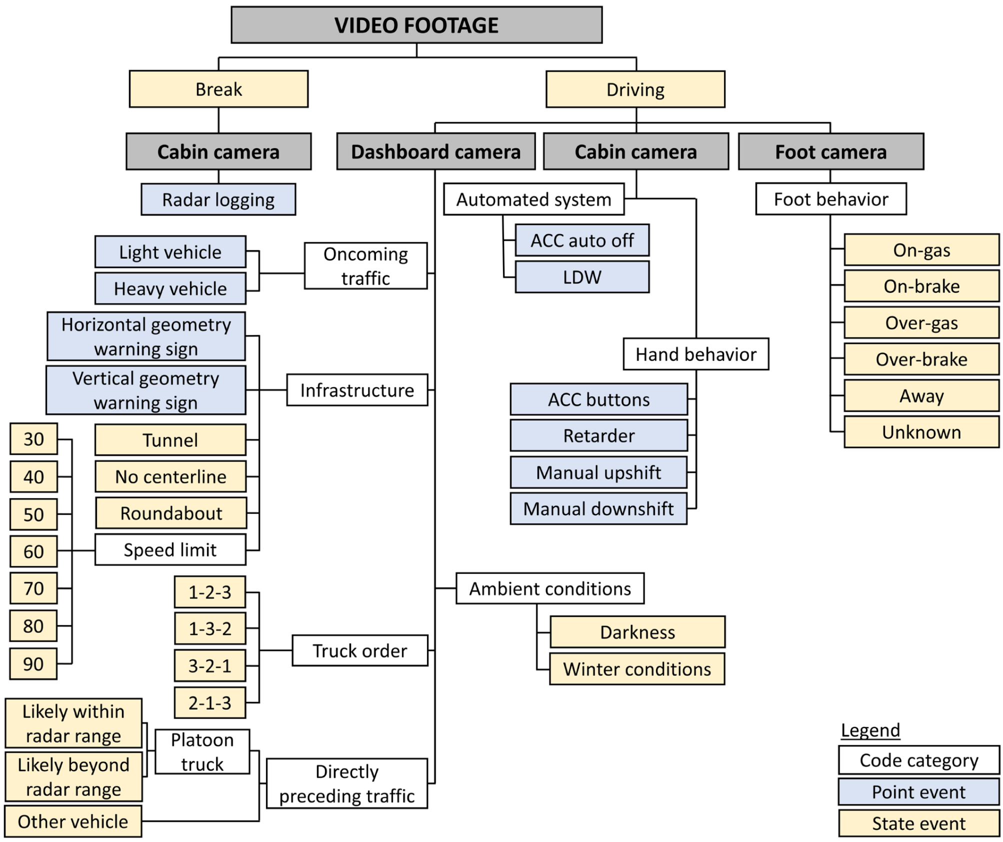

Figure 13: Overview of all BORIS video codes in the Field Study.

Simplified overviews of the video codes were shown in Papers 2 and 3, including only those which were found to provide targeted and interesting results within the scopes of each paper. For instance, *Light vehicles* were not found to affect the truck platoon much, whereas *Heavy vehicles* were wider and more difficult for the platoon to encounter, especially on narrow road sections. The Lane Departure Warning (*LDW*) code was initially included in BORIS as it may suggest the difficulty of the horizontal road geometry, but the idea was short-lived. Dialogue and videos revealed that, due to constant warnings, drivers quickly disabled the feature. Of note, *ACC auto off* refers to situations where ACC disconnected automatically since speed fell below the 15 km/h threshold. Moreover, the *Unknown* foot behavior code refers to periods where the pedal cameras malfunctioned. For all trucks, data from such periods could be affixed using verbal statements made by the drivers, such that no data was lost. Events lists were exported and analyzed in Python (Paper 2) and Excel (Paper 3).

Interviews and Participant Conversations

Interviews were conducted twice with the drivers. Pre-trial interviews were held to elicit information about their background and expectations. Midway interviews were conducted at the end of the first day to have them reflect on their experiences thus far. Pre-trial and midway interviews lasted for 15 and 30 minutes, respectively.

The reflections of the participants during the test were recorded in audio from the cameras. The researchers and organizers also engaged with participants over radio while driving, eliciting discussions during quiet periods. Conversations which took place in truck 1 were generally short and sporadic, while those in trucks 2 and 3 tended to discuss and deliberate about relevant topics and situations for longer periods. These are also the more interesting trucks to have data from, having served as followers for long periods.

Full interviews, alongside relevant statements from in-truck conversations, were transcribed and subsequently analyzed using NVivo 12. The latter dataset was collected in a more natural setting, and therefore better encapsulated real-time reflections. Alongside the statements, transcripts included the person which made the statement, and useful non-verbal context from the videos. A common coding scheme was developed, totaling 29 codes. Altogether, 3,500 relevant statements were coded, comprising an extensive and useful dataset. **Figure 14** shows the 12 codes with the most references. The five top codes comprised 44% of all references. Hence, these issues were widely discussed among the participants.

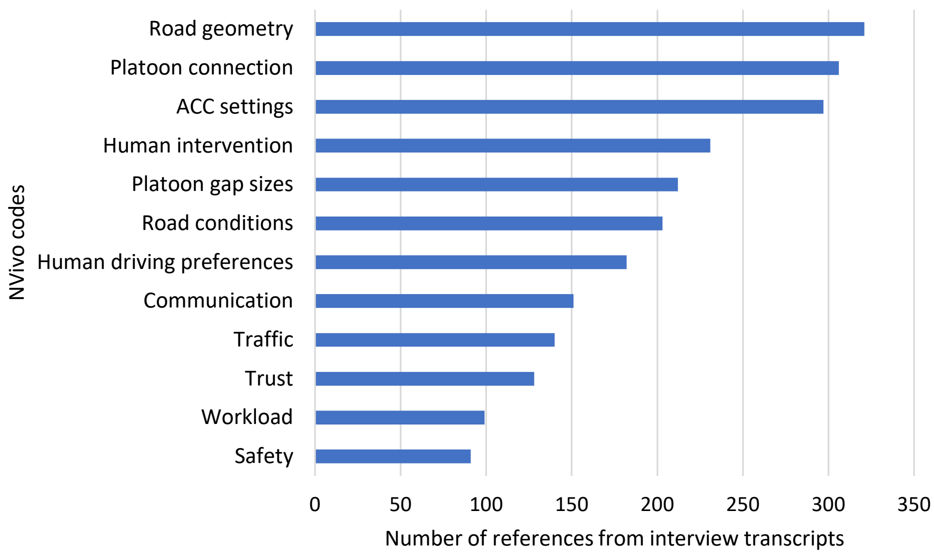

Figure 14: Overview of the 12 codes from the Field Study with the most references.

Road Geometry

The Norwegian road network is digitized in an online repository termed the National Road Database (Norwegian Public Roads Administration, 2023a). Horizontal curvature, vertical grades and road width were extracted from the database to convey the difficulty of the road alignment on the traversed stretch. Radii and grades were binned, and the length of curves and gradients within each bin, were determined. This showed that around 10% of the stretch was comprised of horizontal curves with sub-250-meter radii, and that 6% of its length had vertical gradients exceeding ±7%. Based on publicly available data, this makes it the steepest and most winding road on which truck platooning has ever been tested.

Based on the notion that road standard may impact the speed consistency for the platoon (P. Singh et al., 2018), the same method was used in Paper 3 to extract road geometry data for two smaller stretches. With reference to **Figure 7**, these were located between Storjord and Røkland, and between Innhavet and Ulvsvåg, respectively. Platoon behavior over these stretches was explored using truck speeds from the fleet management system, and inter-vehicle distances as measured by the aftermarket radar sensors.

In short, the Field Study provided hands-on experience with SAE level 1 truck platooning on rural roads, using a mixed-methods approach, culminating in Papers 2 and 3. Paper 2 details experiences with aftermarket tools for collecting inter-vehicle distance data. Finally, Paper 3 summarizes observations from the trial, including findings on speed, fuel use, and driver behavior, as a function of the route and the situations which were encountered.

3.4 Industrial Study

Based on the future prospects of free-agent trucks and platooning with driverless followers, it was considered useful to reflect on future developments in automated trucking at higher automation levels. Specifically, the goal of the Industrial study was to understand the technological, infrastructural and organizational factors which could impact the deployment of such trucks, irrespective of whether they are as lonesome vehicles or if they are configured in platoons.

Over the past years, a handful of Norwegian initiatives have materialized where automated on-road transportation is being tested. Most prominently, a number of passenger shuttles have been used for testing in Norwegian cities (Lervåg, 2020). However, none of these meet the requirements set forth by the NPRA for driving on open roads in normal traffic. In particular, they are unable to read signs or markings, nor are they able to perceive dangerous situations (Hansson, 2020). This may suggest that the deployment of on-road applications is premature, raising the question of whether other applications exist which can provide useful insights for downstream research and deployment of automated trucks on public roads.

Somewhat adjacently, the maritime industry is gradually introducing unmanned ships and passenger ferries (Rødseth et al., 2023), and there are some Norwegian companies developing automated transportation solutions in enclosed areas. Examples are construction machines (Reed, 2019), farming equipment (Viseth, 2021), and rovers for monitoring runways at airports (Nyborg, 2023). Similar applications exist abroad, e.g., the automated container movers at the port of Rotterdam (Vis et al., 2001). Enclosed areas were believed to be less complex than public roads, providing good conditions for deploying automated driving solutions. However, the exact details which make such applications good candidates for autonomy, are not known. There is also little publicly available information from such applications, making it difficult to draw informed conclusions. The aim of the Industrial Study was to change this.

The following subchapters introduce central aspects of the Industrial Study, namely the use-cases which were studied, and an overview of the methodology behind the interviews and analysis.

3.4.1 Use-Cases

Only two Norwegian use-cases exist which are based on modified commercially available trucks, reflecting the nascent state of automation in this context. Early in this doctoral work, the Department for Transport Development at the NPRA had expressed an interest in studying the automation of limestone haulage at the Brønnøy Kalk limestone mine, where Volvo Autonomous Solutions (VAS) is the supplier. The use-case was believed to provide valuable insights towards the ability of automated trucks to handle harsh infrastructural and environmental conditions. Examples include dust, difficult weather, steep and dark tunnels, fog, and winter conditions, comprising aspects which automated driving systems should also handle for safe on-road deployment. Notably, Brønnøy Kalk is the first use-case of its kind in Norway to employ driverless trucks without safety drivers (Volvo Autonomous Solutions, 2023a).

Ambitions first involved studying this use-case in isolation. However, the scope was expanded to look at an additional use-case, namely the Autonomous Snow Removal (ASR) project by airport operator Avinor, at Oslo International Airport (OSL). Including this use-case doubled the sample size. Moreover, it enriched the study significantly, as it allowed for reflections to be made by comparing the operational concepts in the two use-cases.

While VAS involves independent trucks engaging in free-agent automation, the Avinor use-case involves purpose-built, automated trucks operating autonomously in platoon formation. Successive trucks are increasingly offset in the lateral direction, intercepting snow which spills over from the end of the plow of the preceding truck. This is termed an *echelon formation*, and it is often used during winter maintenance operations on multilane roads, and in the agricultural and military domains (EL-Zaher et al., 2012). Resembling truck platooning, this operational concept ties nicely back to the main topic of the thesis. Notably, the infrastructure at OSL is simpler and more controlled than the site at Brønnøy Kalk.

Figure 15 and **Figure 16** illustrate the two operations. The use-cases are similar in terms of scale and complexity, and in the interface between technology and human supervision. They also complement one another in capturing central and rural locations. Both use-cases rely on pre-recorded routes, and are dependent on GNSS positioning using RTK stations and CPOS subscriptions. Both applications also have trucks which can be driven manually. **Table 9** compares the two use-cases further, and **Figure 17** shows their locations. All elements of the table are substantiated in greater detail in Paper 4.

3.4.2 Interviews and Analysis

Interviews were conducted with one representative from each use-case. Each participant was interviewed for three hours, through initial and follow-up interviews. The conversations were transcribed on-the fly and reviewed, anonymizing personal details pertaining to the two interviewees. Transcripts comprised approximately 20 pages. Interviewees were given access to their transcripts before synthesis commenced, to ensure that any proprietary information which may have been unintentionally shared during interviews would be kept confidential.

Owing to the descriptive nature of the Industrial Study, and also its comparatively limited scope, the dataset which materialized was smaller than those from the preceding studies. Hence, NVivo 12 was not needed for thematic analysis. Instead, statements were organized while the manuscript was written. Descriptions of the two use-cases were condensed and contrasted, while retaining the original significance of each remark. A handful of important and contemplative statements from the interviewees were used to structure the paper. The two participants were also invited to read through, suggest changes, and approve of the final version of the publication, to safeguard their commercial interests.

In summary, the Industrial Study used semi-structured interviews to collect data pertaining to two industrial use-cases of automated trucks. The study culminated in Paper 4, which contains a synthesis of each use-case, alongside a reflection on the relevance of the learnings from each use-case towards deployment of automated trucks on public roads.

Figure 15: Stone haulage by VAS at Brønnøy Kalk (Volvo Autonomous Solutions, 2023b).

Figure 16: Snow removal at OSL (Provided by Avinor interviewee).

Table 9: Overview of differences between the two industrial use-cases.

Aspect	Use-case	
	Airport	**Mine**
Application	Snow removal.	Stone transport.
Road surface	Exclusively concrete or paved.	Paved (gravel at crusher).
Conventional infrastructure	Flat, open area. No tunnels and few sharp horizontal curves.	Mostly flat area. Two tunnels, one of which is steep. Some very sharp turns.
Physical roadway adaptations	None.	Wooden lidar reflector walls, digital fences, and stone barriers. Some stretches were widened.
Description once fully operational	Six trucks operating in a platoon. Human operator in lead vehicle, who monitors the operation. Following trucks are unmanned.	Seven trucks operating simultaneously, independently of one another. No humans present in any of the trucks.
Truck details and mass	Assembly with truck, trailer and a connector beam with blower and sweeper unit. 40 metric tons.	35 metric tons when unloaded, versus 95-100 when fully loaded.
Sensors for automation	None.	Radar, 2D and 3D lidar.
Navigation	Purely GNSS-based.	GNSS-based in quarry, 2D and 3D lidar elsewhere.
Susceptibility to inclement weather	Low. No sensors that can be impaired.	High. Lidars struggle in dense snow. Issues with temperature differences inside and outside tunnels, and dust on sensors.
Digital communication and connectivity	4G or 5G cellular signals from two independent carriers.	Non-redundant 4G cellular signal. Repeaters are installed throughout the site.
Emergency stop functionality	Stop buttons on and inside trucks and at air traffic tower.	Stop buttons on and inside trucks and also wearable buttons.
Planning flexibility	Dynamic. Can change driving parameters easily, e.g., routes, lateral offsets and longitudinal spacing.	Fixed. Rerouting requires new lidar signature along the new alignment.
Other traffic participants	Planes, and ground crew in other vehicles and as pedestrians.	Mining company employees in other vehicles and as pedestrians.
Responsible for perception	Mainly lead vehicle (ASR) operator, but also plowing leader and air traffic control, for initiating emergency stops.	Lidar sensors, and partly also wheel loader and crusher operators when the trucks are in the mine or crusher sites.
Vehicle-to-vehicle communication	No. Communication goes via the fleet controller.	No. Trucks do not have awareness of where the others are, until they are detected by the sensors.

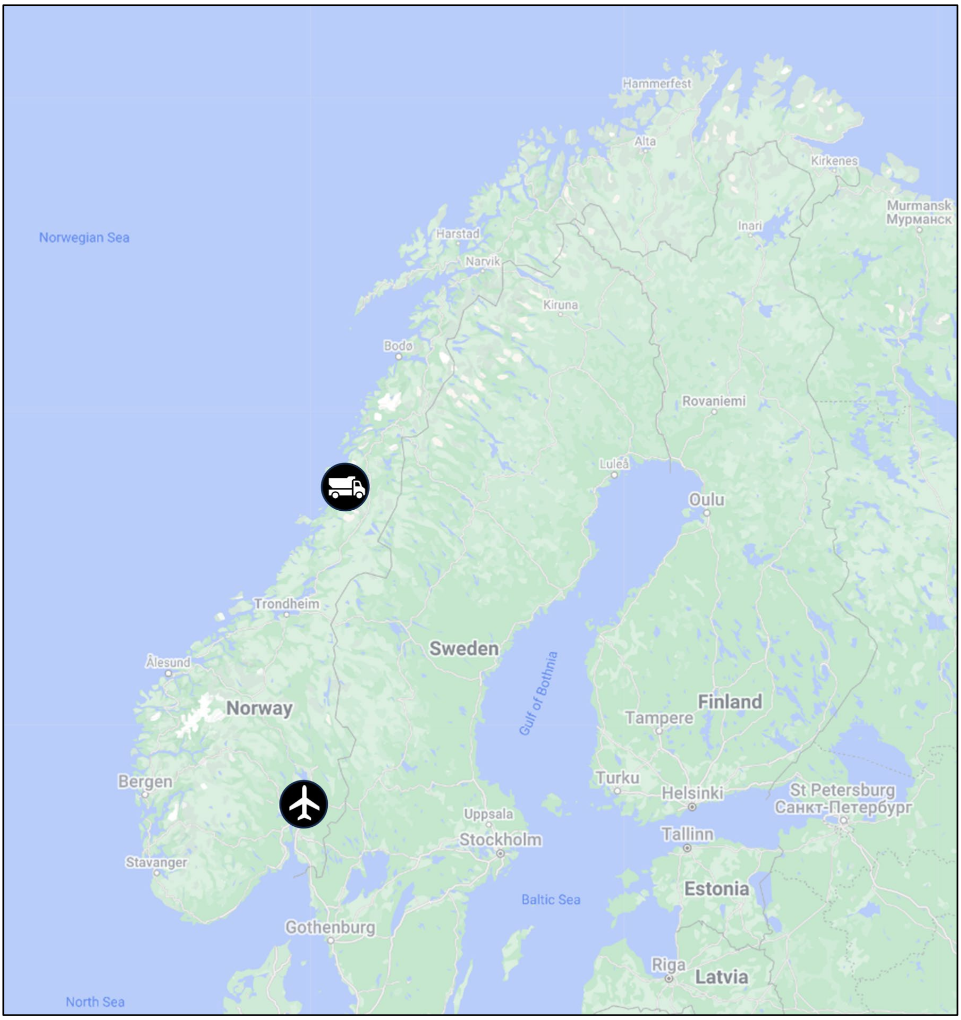

Figure 17: Locations of use-cases. Avinor (southern pin) and Brønnøy Kalk (northern pin).

4 Results and Discussion

This chapter presents and discusses the findings related to the four main themes which emerged, namely *Conventional Infrastructure* (i), *Organization* (ii), *Enabling Technology* (iii) and *Economics* (iv). Since the themes and research questions are related, the research questions are repeated below. The themes are presented in sequence, using findings from the three respective case studies, namely the *Stakeholder Study (i)*, the *Field Study (ii)*, and the *Industrial Study (iii)*. The chapter remarks on factors which were introduced in **Figure 1** in subchapter 1.2.

RQ1. What infrastructural factors facilitate or hinder deployment of truck platooning on public roads in Norway?
RQ2. What organizational factors facilitate or hinder deployment of truck platooning on public roads in Norway?
RQ3. What enabling technologies are needed for truck platooning on public roads in Norway?
RQ4. What economic considerations facilitate or hinder deployment of truck platooning on public roads in Norway?

The case studies are only discussed as they provided results for the current theme. Specifically, the Field Study bypassed organizational hurdles related to planning and matchmaking, which were discussed in the Stakeholder Study. Similarly, it contributed with few economic insights. Following the discussion of findings from relevant case studies, a summary of key findings is provided for each of the four main themes.

4.1 Conventional Infrastructure

All case studies provided the opportunity to study requirements that truck platooning places on conventional road infrastructure, addressing the following research question:

RQ1. What infrastructural factors facilitate or hinder deployment of truck platooning on public roads in Norway?

4.1.1 Stakeholder Study

The stakeholders discussed many infrastructural factors for truck platooning. In support of previous work, motorways were believed to be the most *platoonable* roads (Noruzoliaee et al., 2021), seconded by high-standard rural roads. This was also the order of deployment which was seen as most realistic. Thus, insights are grouped into two sections:

i. Motorways
ii. Rural Roads

Motorways

While motorways emerged as superior candidates, some interviewees believed pushback against motorways might disfavor truck platooning since the motorway network is already limited. **Figure 18** shows a handful of routes which were most frequently brought up by participants as platoonable. The figure was based on many aspects of platoonability, and not just road standard. The thickness of the lines indicates their relative frequency of mentions. Juxtaposed by the motorway network in **Figure 4**, only southeastern Norway sees meaningful overlap. Some interviewees resonated with the recent slowdown in motorway construction efforts, stating that Norway should instead make better use of existing roads and that if truck platooning requires motorways, other solutions to road freight should be explored.

Figure 18: Platooning-viable routes (Eitrheim et al., 2022).

Rural Roads

When discussing deployment of truck platooning on lower-standard, two-way, two-lane roads, interviewees stressed the importance of homogeneous road standard. There was consensus that sharp curves and narrow sections comprise bottlenecks which should be eliminated. Interviewees agreed that routes with decent overall road standard but with sections in need of overhauls, should be prioritized over those where comprehensive refurbishment is needed. They also suggested that roads should be outfitted with passing lanes on steep uphill sections, so truck platoons may travel at slow speeds without encumbering other traffic. Some suggested incorporating freight volumes in road planning decisions, opining that they are now poorly accounted for. In fact, Grünfeld et al., (2020) found that delays on important seafood routes have economic impacts which, if accounted for, could outweigh refurbishment costs aimed at mitigating the delays. Interviewees pointed out that such undertakings would benefit all road users. Regarding larger refurbishments, some interviewees championed the construction of alternating three-lane expressways instead of two-lane, two-way roads, as this would facilitate overtaking of truck platoons at regular intervals, which was seen as vital for acceptance by the motoring public.

Regarding roadside infrastructure for coordination, stop pockets and truck stops were pointed out as essential. Interviewees argued that such elements would also improve conditions for conventional road freight, making them attractive undertakings both in the short and the long term. Some interviewees were positive to the use of ferry terminals for coordinating truck platoons. Others were skeptical since ferry terminals are located in coastal areas where road standard tends to be poorer than elsewhere. While environmental concerns have caused recent pushback towards tunnel and bridge construction, interviewees rightly stated that many ferry replacement projects are underway along coastal main roads, the completion of which will remove the efficacy of ferry terminals for coordination. Interviewees were also skeptical towards operating truck platoons in steep subsea tunnels.

4.1.2 Field Study

The Field Study tested a platoon of three trucks on rural roads in Norway. While drivers in the following trucks used the platooning system without interventions in most conditions, a handful of infrastructural factors for truck platooning were identified. Since the followers operated at SAE level 1, the findings are most applicable to lower-level automation systems. Findings from the Field Study are grouped into two subheadings:

i. *Road Standard*
ii. *Infrastructural Factors*

Road Standard

Figure 19 (*top*) shows the speed profiles for the platoon on two road stretches along the route. Stretch 1 had high road standard, while the standard of stretch 2 was lower. Speeds on the former stretch were higher than those on the latter, and the speed variability on the unfavorable one was more than three times greater.

Due to speed fluctuations, large variations in inter-vehicle distances were observed on the low-standard stretch. This is shown in **Figure 19** (*bottom*). The gaps remained consistent for most of stretch 1, but not for stretch 2. For both followers, the distance variability on the unfavorable stretch was more than twice that for the favorable one.

Generalizing beyond these stretches, the platoon operated favorably on high-standard rural road sections with forgiving alignment. These parts of the route were flat, wide, and void of sharp horizontal curves and frequently alternating vertical gradients. This made the platoon operate harmoniously and in a coordinated manner, with consistent speeds and inter-vehicle distances over longer periods. This is in accordance with findings from Swedish tests (Alam et al., 2015). Nevertheless, this result is unsurprising, as roads with such features conceptually approach the alignment of motorways, which are known to be optimal for truck platooning.

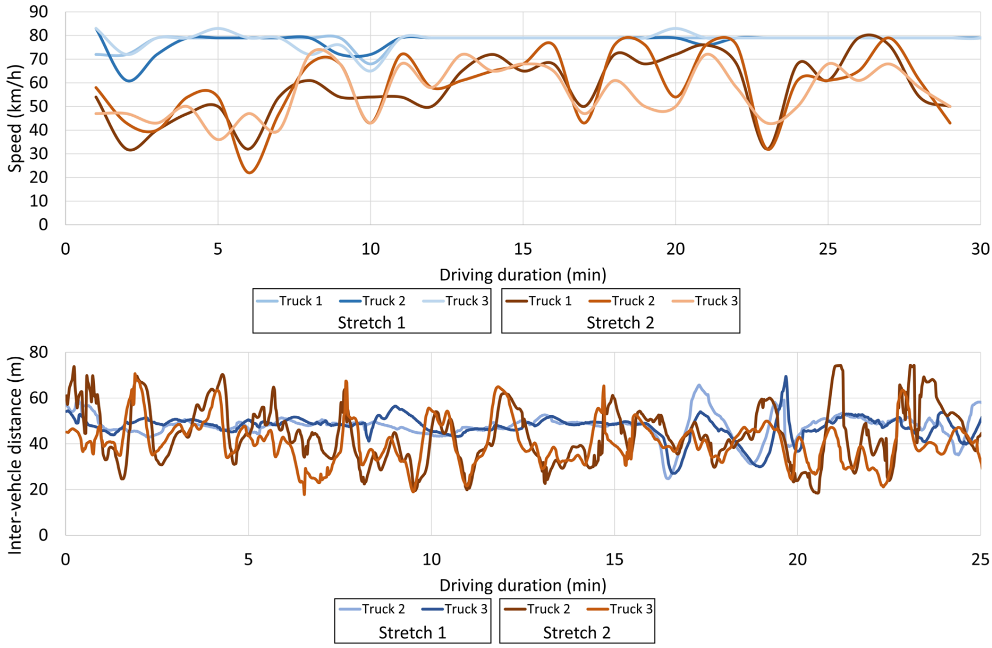

Figure 19: Platoon speeds (*top*) and inter-vehicle distances (*bottom*) for stretches 1 and 2.

The truck platoon in the Field Study drove with an average speed of 62 km/h, despite the most frequent 80 km/h speed limit. Estimates made using digital planning tools, and discussions with former truck drivers with experience from the route, indicated that such speeds are typical also for non-platooning trucks. Hence, low speeds were mostly a property of the geometric features of the route at hand, as opposed to it being a result of the platooning arrangement. The highest platoon speeds were recorded on high-quality sections. Compared to unfavorable ones, favorable stretches also required fewer driver interventions. This suggests initial deployment on high-standard roads, in accordance with the reflections by interviewees in the Stakeholder Study.

Infrastructural Factors

This section goes into further detail regarding specific road infrastructure elements and driving conditions which hindered the platoon. Four types of infrastructural factors were found to hinder the platoon. These were *Vertical Grades (i)*, *Horizontal Curves (ii)*, *Narrow Tunnels (iii)*, and *Winter Conditions* (iv). The two former were particularly prevalent and detrimental, as they caused the platoon to contract and expand as the trucks successively traversed them. These barriers are now discussed further.

Vertical Grades

Due to the large mass of the trucks, their speed dropped significantly during climbs, such that the trucks had to change to lower gears to maintain momentum. While this would also have been the case for non-platooning trucks, platooning was found to necessitate coordinated actions for the ACC-based platooning system to be able to retain the desired distance between the trucks. Gear shifting, however, was an uncoordinated process. The lead driver, who rarely used the ACC system, often shifted gears manually, despite his truck being equipped with an automatic transmission. The followers, who mostly used the platooning system, usually relied on their automatic transmissions for shifting. Hence, the first truck executed more strategically timed downshifts than what the following trucks did, frequently causing them to lag behind, before their platooning systems sped up to close the gap which had materialized.

Uncoordinated downshifting made the ascent erratic for the platoon as a whole, and possibly lead to increased fuel use for the following trucks. This supports Swedish findings (Alam et al., 2015; Turri et al., 2017), where an increase in fuel use was observed during platooning on uphill sections, due to unfavorable gear shifts and other engine dynamics. In fact, these effects even led to harsh, undesired braking during uphill climbs. These effects were also not accounted for by the platooning system in the Field Study. Furthermore, in the Field Study, the effects were likely exacerbated by truck 3 being lighter than trucks 1 and 2, but the exact influence of the weight difference is unclear.

Downhill descents were also erratic, and interventions occurred when the following trucks approached their preceding truck too quickly and too close for comfort. The lead driver was often cited by the followers as being overly cautious in downhills, braking manually, using a combination of the retarder and the brake pedal. When doing so, the gap between the first and the middle truck would shrink, necessitating harsh braking for the middle truck, and even harsher braking for the trailing truck, due to the effects of sensor lag. This effect may also have been amplified by slipstreaming effects materializing. The shrinking gap, combined with high speed, may have caused the followers to experience lower air resistance than what the lead truck did, requiring even harsher braking for the two followers (Turri et al., 2017).

Horizontal Curves

In sharp curves, the followers experienced the preceding truck leaving the field-of-view of the integrated cameras and radar sensors, causing intense acceleration. No longer detecting a preceding vehicle, the truck assumed a clear path, accelerating to comply with predefined settings. When the system regained visibility to the preceding truck, it was now located closer than the prescribed gap size, causing abrupt automated braking. Horizontal curves following steep downhills frequently warranted the following drivers to prepare to intervene, and the following drivers would sometimes preemptively approach the brake pedal or even disengage the system in anticipation. They also experimented with cutting sharp left corners, increasing the odds of remaining connected. While representing a rather creative makeshift solution, this is naturally undesirable from a traffic safety perspective.

While the trucks had lane-keep assist systems installed, all drivers were observed disabling those systems early during the trial. The narrow and winding roads on some sections of the route made it so that the drivers were continuously warned of line breaches. This may suggest that automation at higher SAE levels will be difficult to achieve on such roads, as the steering inputs are demanding, while the physical margins available for maneuvering are small.

Narrow Tunnels

As alluded to in subchapter 3.3.1, many of the tunnels on the Field Study stretch were in poor condition. Specifically, the platoon traversed a handful of tunnels which had insufficient widths to safely facilitate platooning when encountering oncoming trucks. Occasionally, drivers had to maneuver the outer wheels outside of the edge markings to leave sufficient space for opposing trucks to pass. However, such maneuvering left the drivers vulnerable to hitting the curving tunnel ceiling with the roofs of their tractors or trailers. Hence, when encountering oncoming trucks, traffic would slow down to ensure safe passage, at times making the platoon speed drop below the 15 km/h ACC disengagement threshold, warranting manual interventions. Hence, the following drivers often had their right foot ready to brake. Tunnel driving was characterized by shorter inter-vehicle distances, reflecting lower speeds.

Tunnels should be made sufficiently wide to ensure the safety of drivers and cargo, whether they are traversed by platoons or not. No tunnels in the Field Study were subsea tunnels, so the safety of running truck platoons through deep and steep subsea tunnels remains unclear.

Winter Conditions

Fairly strong winds, sleet and wet snow were encountered in the last 15 minutes of the test. While the lead driver was already driving manually, the middle driver quickly decided to disengage the ACC system. While the rearmost driver kept the ACC-based platooning system active, he experienced this period as very tense, requesting the support vehicles to warn them of oncoming trucks. He was also worried about harsh longitudinal movements when the truck was automatically accelerating, braking, and engaging neutral on the slippery road, in order to maintain the desired distance to the preceding truck.

While the ACC-based platooning system was equipped to disengage automatically in slippery conditions, below some threshold value for tire friction, this never happened, presumably since the drivers chose to intervene first. On slippery stretches with good forward visibility, the lead driver chose to maneuver his truck laterally on the road, partway over the centerline markings, such that his tires drove on strips of the roadway with bare asphalt, as opposed to sleet, and the following drivers did the same. The skepticism of the drivers for platooning on slippery roads supports statements by the stakeholders in the first study, where such conditions were also believed to be challenging. Still, findings from the Field Study towards platooning in winter conditions were very limited, and this area needs more research.

4.1.3 Industrial Study

The Industrial Study explored two use-cases of automated trucks on enclosed areas, as such applications may inform infrastructural needs for truck platoons and free-agent automated trucks, on public roads. Subchapter 1.1.3 cited presumptions that an automated road freight system would entail a tighter link between vehicles, infrastructure, and digital systems (OECD Publishing, 2023, p. 8), and the Industrial Study uncovered several elements in support of this notion. Findings were grouped in three subsections:

i. *Infrastructural Modifications*
ii. *Maintenance*
iii. Closed Areas

Infrastructural Modifications

The Avinor use-case involves automated trucks moving in platoon formation to clear snow from runways. The on-site infrastructure is comprised of large, paved areas, access to which is strictly monitored by personnel in the air traffic control tower. The location required no conventional infrastructure modifications to accommodate the automated trucks. The use-case at Brønnøy Kalk differs, involving mostly unsupervised free-agent trucks driving between two locations, separated by long roads with tunnels, vertical grades, and horizontal curves. While both applications introduced staging areas to ready their automated trucks before each shift, the site and the environment at Brønnøy Kalk more closely resembles the conditions which automated vehicles on open roads may face. Hence, Brønnøy Kalk provided the key inputs for the theme in question.

First of all, areas at Brønnøy Kalk which did not provide sufficient texture for navigation, were instrumented with lidar reflector walls, as shown in **Figure 20**. A stockpile was also introduced, representing another physical addition to the on-site infrastructure. The stockpile is a buffer of limestone which is constantly supplied with rock using wheel loaders, serving to decouple the automated trucking operation from the shifting blast sites where the rock is mined. Furthermore, digital fences were introduced, wirelessly terminating the operation of all trucks if breached, and physical barriers in the form of large and heavy stone blocks contain the trucks within their designated areas in case of severe malfunctions.

Figure 20: Lidar reflector walls at Brønnøy Kalk (Volvo Autonomous Solutions, 2023b).

Maintenance

The linking of vehicles, infrastructure, and digital systems was also encountered in discussions relating to winter maintenance. Specifically, it had been debated whether Brønnøy Kalk or VAS should bear the costs for snow plowing and the removal of ice build-up on lidar reflector walls in tunnels, subject to the capabilities of the automated system. Similar debates, albeit more difficult, are likely to materialize during on-road deployment of automated vehicles.

Closed Areas

Both interviewees underlined the benefits of closed areas for development, unencumbered by external actors. This reinforces previous findings that deployment of automated vehicles on public roads could be facilitated by testing on closed-access facilities. An example of such a facility is the Asta Zero (Active Safety Test Area) test track in Southern Sweden (Paranthaman et al., 2018). Such facilities comprise valuable conventional infrastructure in their own right, and they may emerge as key supplements to real-world testing. This also suggests that routes for automated trucks may need modification, such that they approach the features of closed areas. However, the viability of this approach, as opposed to improving the technological systems which underpin automated operations, remains unclear. This is further outlined in discussions of the remaining themes.

Summary of Conventional Infrastructure

Both the Stakeholder Study and the Field Study support the hypothesis that truck platooning is most feasible on high-standard roads with homogenous features. Since such roads are scarce in Norway, truck platooning may be difficult to implement. In the Field Study, steep vertical gradients caused the platoon to expand and contract, and uncoordinated gear shifts exacerbated this issue. In sharp curves, distances were too large for the sensors to retain field-of-view to the preceding truck, causing abrupt driving behavior by the ACC-based platooning system. Though based on limited observations, tunnels and winter conditions proved difficult for the platoon. The Industrial Study showed some examples of infrastructural modifications to facilitate automation at higher SAE levels, but their applicability for use on public roads is unclear. Hence, the main infrastructural take-away from the Industrial Study likely relates to the benefits of constrained areas for testing and development of automated driving systems, unincumbered by external actors.

4.2 Organization

The Stakeholder Study and the Industrial Study provided findings to address the second theme, namely organization. The former study provided suggestions for organizing truck platoons in Norway, and the latter one identified organizational means which were undertaken to enable automated trucks at enclosed sites. Together, the studies addressed the following research question:

RQ2. What organizational factors facilitate or hinder deployment of truck platooning on public roads in Norway?

4.2.1 Stakeholder Study

The stakeholders reiterated previous findings that truck platooning requires many organizational changes to become feasible at a societal scale. The findings were grouped in six subsections:

- i. *Routes, Volumes and Hubs*
- ii. *Matchmaking and Timeframes*
- iii. *Competition and Asset Turnover*
- iv. *Waiting for a Partner*
- v. *Modal Shares and External Traffic*
- vi. Restructuring

Routes, Volumes and Hubs

All interviewees acknowledged that truck platooning requires the existence of a sufficient number of trucks heading in the same direction, during similar time frames. Different solutions were discussed to obtain sufficient volumes. For one, shippers found it unlikely to start platoons directly from their production facilities, as they are typically optimized to cater to and dispatch trucks separately. Similar statements were voiced by the rail terminal representative, as there is no space available for coordination on-site. Hence, this approach would be unsuccessful.

Instead, interviewees suggested organizing platoons from hubs located at key intersections on high-volume routes, as was also suggested by Larsen et al., (2019). Trucks would enter such routes from local roads and aggregate the total number of trucks available to partake in platoons. Some pointed out that, currently, convoys of trucks often form along main freight corridors, and some of the trucks that take part in them tend to use gaps that are rather short, presumably to capitalize on the fuel savings associated with tailgating (Jessa, 2015). On such routes, platooning could be feasible, while potentially also making existing and undesirable tailgating behavior safer.

Matchmaking and Timeframes

Dialogue between carriers was identified as an enabler for platooning, as carriers could agree to dispatch trucks such that they would intercept one another. Interviewees also recognized that such agreements could involve different timeframes of upfront coordination. While some were positive to carriers cooperating to organize platoons, others brought up the difficulty in coordinating even simple ride-sharing schemes with colleagues.

The number of trucks with similar routes required for adoption at scale remain undetermined. However, interviewees believed this number may differ between routes, subject to the distances of typical shipments, and the value of cargo which tends to be shipped there. Interviewees also suggested that the organization of platoons may benefit from the Norwegian road network providing few alternative route choices, such that routing may pose less of an issue in Norway, versus countries with more options, as also discussed by e.g., Noruzoliaee et al., (2021). The interviewees also suggested that shipments with lower-value, non-perishable cargo, may be most inclined to wait for a partner.

Further, interviewees believed that matchmaking software could simplify coordination and distribute savings between carriers. Known as *platooning service providers* (Larsen et al., 2019), one participant described it as *Tinder for trucks*, and this analogy was used in all subsequent interviews to intuitively convey the purpose of such systems. Stakeholders suggested that engine-to-weight ratio should be considered when pairing trucks, as also was exemplified by the weight differences among the trucks in the Field Study. As previously stated, some believed that features of the cargo should be included, such as its time sensitivity, and some remarked that trucks with dangerous goods should not be allowed to partake in platoons.

Respondents were uncertain whether such matchmaking software currently exists. It was also seen as unclear who should own and operate it, but they agreed that ownership should ensure fair treatment of all carriers. While some envisioned such software as an ad-hoc system which could streamline chaotic logistical operations, others saw it as more realistic to coordinate platoons hours or days in advance. The carriers stated that goods are allocated to trucks and drivers on a 1- to 2-day notice. Although purchase orders from shippers may be subject to last-minute changes, this constitutes the planning horizon for upfront organization of platoons. Hence, the interviewees discussed all three matchmaking arrangements which were defined by Bhoopalam et al., (2018) and discussed in subchapter 2.1.4.

Competition and Asset Turnover

Some interviewees believed platooning may be hindered by the competitive nature of the trucking industry. Old tales were presented which illustrate such adversarial practices. For one, some carriers used to save costs for brake pads by instead wearing out brakes of a third-party trailer for which they did not carry financial responsibility. Some interviewees believed that carriers may be unwilling to forego profits to reduce costs, suggesting that incentives could be needed to persuade carriers to partake in the collective effort to deploy platooning.

However, competition may also lead to an unexpected organizational enabler for platooning. In order to remain competitive and retain drivers, one interviewee stated that carriers in Norway replace trucks every 3-7 years, juxtaposing the trucking industry to other freight asset owners. Specifically, logistics companies which own fleets of ships, trains, or planes, may do so for many decades, resulting in slower adoption of new technologies.

Waiting for a Partner

The interviewees stated that roads with low truck volumes may require waiting for a partner, introducing friction for carriers. Hence, they believed that the main freight corridors should be prioritized for platooning, as such routes are most likely to provide sufficient truck volumes to ensure low wait times, increasing carrier acceptance and lowering participation costs. These roads also tend to have higher road standards. Interviewees mostly agreed that ferry terminals may serve as starting points for platoons. Trucks can meet there at zero marginal cost and coordinate their joint departure after disembarking. The same was suggested for customs offices at border crossings, particularly if trucks arrive there outside of opening hours.

Albeit speculative, waiting times on rural roads may be reduced in the future through increased road freight, stemming either from organic growth, or from a modal shift induced by platooning. As organic growth was discussed in subchapter 2.2.1, revised projections indicate a 56% to 68% increase in road freight between 2020 and 2060 (Handberg et al., 2024, p. 3; Madslien et al., 2023, p. v). Furthermore, the goods transfer objective was scrapped from national transport policy objectives after these revisions were made (Norwegian Ministry of Transport, 2024, p. 50), such that the effects of organic growth may be even more sizeable. Any modal shift induced by platooning would only add to this effect, both trends serving to lower waiting times for potential platooning partners at hubs or terminals.

For routes void of ferries, customs offices, or similar features, stopping would be required only to cater to the basic needs of drivers, and to comply with driving time regulations. With respect to the latter, carriers stated that drivers may run the risk of depleting their tachograph by waiting for long periods, as shipments are planned such that available time is fully utilized. For hubs in remote areas, carriers also stressed the *variability* of waiting time. For routes where variability is high, carriers and drivers might be less inclined to wait for one another. To this effect, preliminary findings suggest that some of the long-haul corridors for road freight between Oslo, Bergen, and Trondheim, have shorter temporal variability than others (Hovi et al., 2018, p. v), making them strong candidates for further research on platooning viability in Norway.

Modal Shares and External Traffic

A few interviewees believed that truck platooning may threaten political objectives for goods transfer from road to rail and sea, undermining traffic safety objectives. They were concerned that truck platooning may outcompete other modes for certain routes and shipments, and thereby induce added demand for road freight, which may in turn cause more accidents where trucks are involved. Others suggested organizing platooning so its negative effects on external traffic is minimized. For instance, truck platooning could be introduced gradually, only on certain routes, in certain time periods, or in one travel direction at a time. It could also be organized only during periods of the year which are not subject to problematic winter conditions. Platoons could also be limited in length, such that they consist of at most two or three trucks.

One interviewee believed that the public, if presented with the prospect of truck platooning, may be intimidated by a mental image of encountering vast numbers of partially robotic trucks dominating the roads. Instead, he made the case that organizing trucks into platoons would group them together, causing motorists to face fewer separate interactions with oncoming trucks, with the potential to improve traffic safety. By the same token, platooning may also *absorb* induced volume demands from a potential modal shift. Motivated by the Norwegian Ministry of Transport recently relinquishing the goods transfer objective, truck platooning could be postulated as a solution to minimize adverse impacts of the trucking industry related to traffic safety and greenhouse gas emission. Some interviewees viewed automation as a trend for all vehicle types, and postulated that, if such technology were to become available in passenger cars, they could be incentivized to join truck platoons, instead of overtaking them. In addition to the implied traffic safety benefits, this could limit the need for physical refurbishments aimed to facilitate safe overtaking.

Restructuring

Interviewees suggested that platooning with manually driven lead trucks, and followers at different levels of the SAE scale, could enable different types of restructuring of the industry.

With following trucks at SAE level 3, following drivers may perform other tasks during driving periods when they are not required to pay attention. For instance, this time could be used to coordinate later shipments. Trucks capable of such automation could also enable drivers to rotate positions in the platoon, maximizing platoon-wide travel distance, subject to the total available driving time. Resembling the double-manning concept suggested by Stehbeck, (2019), this could enable groups of trucks to reach their destinations faster. Interviewees found such prospects interesting but unrealistic, given the current regulatory and technological landscape. Some interviewees related this to the practice of organizing long shipments where drivers are replaced along the route as their driving time runs out. This is often the case for shipments destined for Northern Norway.

With following trucks at SAE levels 4 or 5, stakeholders believed that truck platooning could enable a restructuring whereby displaced long-distance drivers operate as feeders between trucking hubs and local areas. This approach is already employed by most start-up companies in automated trucking, which tend to focus on hub-to-hub applications along motorway corridors (Sjoberg, 2022).

4.2.2 Industrial Study

The Industrial Study identified many organizational enablers and barriers for automation and provided grounds for reflections towards open roads. Findings were grouped in five sections:

i. *Simplicity and Oversight*
ii. *Few and Coordinated Actors*
iii. *Interactions with External Actors*
iv. *Converging Trends*
v. *Flexibility and Planning*

Simplicity and Oversight

In both industrial use-cases, infrastructural and organizational simplicity were identified as clear enablers for automation. The Avinor use-case, in particular, was advantaged in both regards. With respect to organizational simplicity, the oversight and coordination by air traffic control rendered negligible the risk of encountering obstacles during automated operation. Hence, vehicular sensors, such as radar, lidar and cameras, were considered unnecessary, making the use-case technologically simpler than would have been required in more complex operational environments, such as the one at Brønnøy Kalk, or those encountered on open roads. The ASR operator in the lead truck at Avinor is responsible for fallback if obstacles were to appear ahead of the platoon, comprising an additional organizational enabler. The Avinor representative was positive towards road traffic control centers operating more like airport control towers. While this has been suggested by others, e.g., Alam et al., (2015), Ulrich et al., (2020) and Mårtensson et al., (2018), the realism of this idea remains unclear.

While it has already been mentioned under the topic of conventional infrastructure, the introduction of the stockpile at Brønnøy Kalk may also be regarded as an organizational enabler. Specifically, it decoupled the automated operation from the irregular activity of rock mining, which lent itself poorly to implementation in the planning algorithm. In related matters, Brønnøy Kalk, in particular, had to introduce systematic regimes for staging routines and vehicle maintenance. These routines were less stringent prior to automation. Hence, such regimes may also be required for automated trucks on public roads.

Few and Coordinated Actors

In addition to the aforementioned organizational enablers, both use-cases provided favorable conditions in terms of having only a few parties involved. Avinor had partnered with two companies, one for supplying hardware, and one for delivering the autonomous control platform. Similarly, Brønnøy Kalk had partnered only with VAS. Therefore, it stands to reason that automation becomes easier to facilitate, the fewer stakeholders are involved. Similar conclusions were drawn by Sjoberg, (2022), who stated that closed sites and few stakeholders are enablers for autonomy.

Stakeholders in road freight are highly fragmented, suggesting that implementation is going to be difficult and time-consuming, possibly despite technological and regulatory advances. It follows that reducing the number of stakeholders, or at least streamlining them, may enable automation. The establishment of an interdisciplinary forum for automated road freight seems pertinent. For instance, this forum could mirror the industry network for winter operations (Norwegian Public Roads Administration, 2023c), which brings together stakeholders for exchange of knowledge. Commercial actors could be encouraged to share learnings from testing efforts, and structures could be set up to incentivize constructive dialogue.

Interactions with External Actors

Some interviewees in the Stakeholder Study identified encounters between motorists and truck platoons as potentially problematic. The VAS interviewee brought up a similar issue, namely the organizational hurdle of facilitating safe interactions between automated trucks and external actors. Specifically, as automation scales, either geographically or in the number of enabled vehicles, actors other than employees who are familiar with the vehicles, will interact with them increasingly often. This will occur either by necessity, or by choice.

Specifically, the VAS interviewee cited drills with local fire brigades for external personnel to learn how to safely approach the trucks in case of emergency responses. This suggests that safe deployment on open roads hinges upon intuitive and standardized procedures for human-vehicle interaction. This is especially the case in locations where individuals may interact directly with the trucks, for instance in staging areas and parking lots. Ensuring safety in most foreseeable situations will be resource-intensive, and more research is required to facilitate the necessary developments. While this is less relevant for fully manned truck platoons, it is pertinent for platooning with driverless followers, and even more so for free-agent single-vehicle automation.

Converging Trends

The project managers from both industrial use-cases described deployment scenarios related to autonomy as an enabler for electrification and downsizing. Specifically, trucks are currently made as large as permitted by regulations, to maximize the load which each driver can haul. Automation upends the current objective. Since drivers are no longer needed, optimizing per-driver payloads is less of a priority. This facilitates the use of smaller trucks, which again is an enabler for electrification. The VAS interviewee cited prospects of electrified and downsized trucks for hauling rocks in mines, and the Avinor representative described a future where runways at smaller airports could be autonomously cleared of snow prior to departures, using small and electrified sweepers who run continuously, at low intensity. This was juxtaposed with the current situation, where large machinery is used intensively, shortly before flight movements, to minimize payroll costs for machine operators.

For public roads, downsizing may suggest studying trucks and passenger cars more holistically, as opposed to regarding them as two different transport modes. Electrification of trucks was also discussed by interviewees in the Stakeholder Study. Since electrified trucks are emission-free during their usage phase, some interviewees believed that electrification may weaken political objective to transfer road freight to other modes, as this objective is partly motivated by emissions reductions. The objective is also partly motivated by traffic safety. However, downsizing could make encounters with trucks less intimidating, and also safer, by reducing the difference in mass, and hence also kinetic energy between vehicles during collisions. Nevertheless, as the cost of batteries keep declining, downsizing may not be strictly required to enable electrification of trucks. However, small trucks need fewer batteries, perhaps accelerating the transition. Electrification could also facilitate smoother operation of truck platoons on low-standard roads, as it removes the destabilizing effects of gear changes which were experienced in the Field Study.

Flexibility and Planning

The interviewees from the industrial use-cases acknowledged that the *operational flexibility* of their solutions have changed due to automation. On one hand, flexibility is increased, in terms of enabling dynamic scaling based on variable demand, allowing for round-the-clock operations, irrespective of driving regulations. On the other hand, automated operations are likely to be more susceptible to externalities which cannot be controlled for, such as cellular outages or bad weather. Nevertheless, and especially in the case of Brønnøy Kalk, weather-related events could be accommodated by running the automated operation more intensely prior to or following them. Hence, on public roads, automation will likely introduce complexity, tighter dependencies, and move operational decisions upwards in the planning hierarchy, to more tactical and strategic planning horizons (Michon, 1985, p. 489).

Summary of Organization

The Stakeholder Study indicates that truck platooning hinges upon many organizational factors. Specifically, it requires a certain number of trucks headed in the same direction, along the same road, ideally at the same time, and at regular time intervals. To achieve sufficient truck volumes, truck platooning could be organized from hubs along busy road freight corridors. Other ideas involve commencing truck platoons at ferry terminals and customs offices. Many destinations in Norway have few alternative routes, causing natural funneling of trucks. On low-volume routes, trucks may have to wait for partners to form platoons, comprising a barrier for deployment. On such routes, the value and time-sensitivity of onboard cargo is relevant. The same is true for the variability of waiting time, as unpredictable timing makes planning difficult. Software may help, but it is unclear whether a turnkey solution exists. Platooning may also be hindered by the competitive nature of the trucking industry and its short planning horizons. Conversely, high asset turnover among Norwegian carriers may expedite the deployment of platooning technology. Truck platooning may be assisted by forecasts of increasing road freight volumes, and may in some sense serve to absorb any induced volumes, leading to fewer individual interactions between external vehicles and oncoming trucks.

The Industrial Study broadened the scope into higher automation levels, with slightly different organizational needs. While the trucks at Avinor in some sense engage in platooning, they are not subject to the real-world struggles of finding partners to platoon with. Nevertheless, this use-case clearly suggests that simple infrastructure and central oversight are enablers for automation. As illustrated by Brønnøy Kalk, automation is feasible also in areas with more demanding infrastructure, as long as it is decoupled from irregular activities, such as rock extraction. This supports Litman (2023), who stated that the predictability of travel patterns for trucks makes them good candidates for automation. Initially, closed sites appear to be enablers for automation. However, both use-cases bypassed what is arguably the most difficult issues facing on-road automation, namely the unpredictable nature of human behavior. Hence, it remains unclear whether learnings from closed areas are actually helpful for deploying automated trucks on open roads, and much work is needed to ensure that humans and automated vehicles can co-exist. Manned truck platoons are simpler in this regard, owing to the presence of at least one accompanying human. The Industrial Study also suggests that the difficulty of achieving safe and reliable vehicular automation increases with the number of stakeholders involved. Since the organizational landscape for road freight is complex, significant effort will likely be required to align stakeholders.

4.3 Enabling Technology

All three case studies provided suggestions for the enabling technologies which facilitate truck platooning, but they did so in slightly different ways. While interviewees in the Stakeholder Study focused mostly on the technologies which enable the coordination of truck platoons, the Field Study addressed features of the ACC-based platooning system which was installed in the trucks. As for the two previous themes, the Industrial Study provided insights into the technological characteristics for higher-level automated driving systems destined for use on closed areas, some of which may also be applicable for automation on open roads. These findings addressed the following research question:

RQ3. What enabling technologies are needed for truck platooning on public roads in Norway?

4.3.1 Stakeholder Study

The findings from the Stakeholder Study related to enabling technology were grouped into two sections:

i. *Technological Maturity*
ii. *Matchmaking*

Technological Maturity

Stakeholders agreed that the automation systems involved in truck platooning must be proven technologically reliable before platooning may be deployed as part of normal business operations. Most interviewees were skeptical that the technology available today is sufficiently mature, and they saw the prospect of higher-level automated driving on public roads as unlikely in the short to medium term. This mirrors findings by Engström et al., (2019).

Matchmaking

With regards to enabling technologies, interviewees in the Stakeholder Study tended to focus mostly on requirements for the digital systems for matchmaking and for platoon scheduling, as opposed to focusing on driving automation systems. From the perspective of enabling technology, it was frequently discussed what information the matchmaking system could include to provide suitable matches. Some suggested modelling this solution after the Automatic Identification System (AIS) used in the shipping and aviation industries. Although it was its main focus, the ENSEMBLE project also acknowledged the need for matchmaking systems, also suggesting trucks to be matched based on vehicle compatibility. The importance of such systems being interoperable across trucks from different manufacturers was also underlined and underlined (Schmidt & Mascalchi, 2022, p. 10).

Trucks from different manufacturers have different fleet management systems, and some interviewees suggested organizing them through a universal data sharing layer and integrating them with matchmaking solutions. Real-time monitoring and status for critical components, such as brakes, could be implemented, providing data for calculating applicable operational control regimes within platoons, subject to the physical properties of the partaking trucks. Examples of such characteristics are mass, engine power and gear ratio (Alam et al., 2015). To this effect, the rail terminal representative suggested drawing inspiration from the logistical management systems used for organizing rail freight in Norway, as it accounts for similar characteristics.

4.3.2 Field Study

The Field Study contributed with two categories of findings towards enabling technology:

i. *Following Distances*

ii. *Vehicle-to-Vehicle Communication*

Following Distances

The technology which enabled platooning in the Field Study was based on ACC and operated at SAE level 1. The system had predetermined distance settings which limited how short the following distances between trucks could become. Drivers agreed to the configuration of distance settings over radio, but they were free to change them at their own volition at any time. Distance settings were often chosen at two bars, as opposed to one, which represented the shortest possible following distance.

As discussed in subchapter 2.1.3, truck platooning is often championed for its potential to reduce fuel consumption. However, data from fleet management systems in the Field Study suggest that no fuel savings were achieved. This is not surprising, as the inter-vehicle distances were rather large. Radar data revealed that the two following trucks maintained an average of approximately 40 meters to their respective preceding trucks, which is too far to unlock savings from slipstreaming at the available speeds. The drivers in the Field Study only seldomly chose to employ the setting corresponding to the closest following distance. This may support the suspicions by some of the interviewees in the Stakeholder Study, who questioned the realism of platooning on rural roads. This is further substantiated in subsequent discussions grouped under the economic theme.

Vehicle-to-Vehicle Communication

Subchapter 2.1.5 introduced the concept of vehicle-to-vehicle communication, referring to wireless networks which facilitate the transfer of driving commands from the lead truck to the preceding trucks simultaneously, and in real-time. Such communication may improve the performance of platooning systems by allowing the trucks to drive closer together. This functionality exists, and it was in fact available in the three trucks which took part in the Field Study. It was not used, however, as a frequency license was not obtained from the Norwegian Communications Authority. Vehicle-to-vehicle communication may smoothen speed profiles for the platoon on ascents and descents, potentially unlocking fuel savings. Furthermore, it may address the issues related to the loss of connection to the preceding truck during traversal of sharp horizontal curves. Hence, obtaining such a license represents a natural next step for testing truck platooning on Norwegian roads. Prospects for fuel savings are unclear, however, as also the EMSEMBLE project concluded with platooning as a support function producing negligible fuel savings (Schmidt & Mascalchi, 2022), despite communication between trucks and road conditions being more favorable.

4.3.3 Industrial Study

The Industrial Study gave insights into the enabling technologies which underpin applications of automated trucks on enclosed areas. The findings and discussions were grouped as follows:

i. *Localization and Object Detection*
ii. *SAE Levels and Safety Drivers*
iii. *Maturity and Transfer Potential*

Localization and Object Detection

In terms of the tasks of localization and object detection, the two industrial use-cases operate in different ways, but they also have several similarities. The applications are described and discussed separately before drawing parallels between them.

At Avinor, pre-planned digital routes are drawn on a map of the airport which was created using aerial and satellite imagery. Automation at Avinor increased lateral positioning accuracy, reducing the need for overlap between successive trucks, from 0.5 meters in manual plowing, to only 2-5 centimeters. Such improvements allude to the potential for similar enhancements in more complex environments in the future. Regarding object detection, the trucks at Avinor exclusively use GNSS for localization, and they have no onboard sensors for object detection. Hence, they are unable to detect or stop for obstacles. In fact, the trucks are even unable to detect their respective preceding truck in the platoon, leaving the task of collision-avoidance to the autonomous control platform.

The route at Brønnøy Kalk was also pre-mapped, not by overhead imagery, but by recording the lidar signature of the surroundings. This produced a digital HD map of the scene, albeit a simpler version than was introduced in subchapter 2.1.5 for the purpose vehicle automation on open roads. The lidar recording is distributed to all trucks, which use it as their reference map. If the surroundings are subject to large changes, the trucks may no longer be able to localize themselves. If so, the trucks stop in place, and they must be manually driven until a new lidar recording is distributed. At Brønnøy Kalk, both lidar and GNSS are used for localization and navigation. Lidars are needed since GNSS positioning does not function inside tunnels, which comprise the bulk of the route. Lidars are also used to detect and stop for obstacles. This is needed at Brønnøy Kalk, since the area is subject to less strict surveillance than what is the case at Avinor.

Due to the aforementioned reasons, in neither use-case are the trucks able to deviate from their planned paths to automatically circumvent obstacles. Moreover, in both applications, communication with the trucks relies on cellular connectivity. For both use-cases, communications run between each truck and a central control system, such that the trucks do not communicate directly with one another. This is illustrated for the Avinor use-case in **Figure 21** *(left).* For localization, both applications subscribe to the CPOS service by the Norwegian Mapping Authority, as introduced in subchapter 2.1.5. **Figure 21** (*right*) illustrates the installation of a CPOS base station. Currently, the service has 5,000 domestic users, but it is not sufficiently scalable to handle requests from a significantly larger number of receivers. Based on the reliance of both use-cases on the service, it may need to be scaled up. Installation could commence along the most automation-feasible routes, as suggested by Ulrich et al., (2020). Furthermore, the private sector could contribute with providing similar services, as suggested by Arnesen et al., (2022).

Figure 21: GNSS and communications (*left*), and CPOS base station (*right*) at Avinor.

SAE Levels and Safety Drivers

In Paper 4, the use-case at Brønnøy Kalk was denoted as an automated system at SAE level 4, owing to the on-board object detection capabilities of the trucks. However, difficulty arose when attempting to place the Avinor application within this taxonomy. During initial testing, safety drivers had been present in all trucks in the platoon. Eventually, these will be gradually phased out, leaving only the ASR operator in the lead truck. The Avinor use-case was arguably placed at SAE level 3 since the ASR operator is responsible for fallback if obstacles are encountered. However, since the possibility for running into obstacles is basically nonexistent, fallback for this purpose is mostly irrelevant. Conceptually, it could therefore also be denoted as a system at SAE level 4. The Avinor representative stated that the automated system is configured such that the ASR operator could technically be situated elsewhere in the platoon, or even someplace beyond it. However, the choice made to keep the ASR operator in the lead truck, tipped the scale towards placing the system at SAE level 3.

The role of safety drivers in automated systems at SAE level 3 is known to be a challenging topic, as requirements for fallback and situational awareness are unclear (Llorca, 2021, pp. 2–3). This was also pointed out by the Avinor interviewee. Specifically, since obstacles are rare, he cited that safety drivers run the risk of losing focus. He also cited difficulties in defining criteria for when the automated driving system is considered sufficiently safe to be able to remove safety drivers from the operation. In fact, he stated that retaining safety drivers might even be *unsafe*, as it exposes them to risks from sudden operational shutdowns. Hence, these judgements are difficult, and they will likely be even more so on open roads.

While they do not aim to do so, the SAE levels do not incorporate the slow and meticulous development process required to advance between automation levels. Since development periods for automated driving systems are bound to be lengthy and characterized by a multitude of challenges, a more granular classification system could be designed. The classification system could also incorporate the suggestion by Engström et al., (2019) of step-wise, and iterative deployment of use-cases. Finally, it could attempt to encompass remote and distributed oversight, seen in both industrial use-cases, as such solutions may become increasingly relevant in the future.

Maturity and Transfer Potential

Based on publicly available media reports (e.g., Daler, 2021; Hildonen, 2021), the Avinor use-case was first believed to resemble open-road platooning, albeit at slower speeds, and in a more controlled operational environment. According to the definition of platooning, the trucks do move successively and in a coordinated manner, and they boast automated systems which are likely to facilitate the removal of drivers in the following trucks in the foreseeable future. However, the Industrial Study showed that the comparison to open-road platooning may not be entirely justified, owing to the internal workings of the Avinor system. In open-road platooning, partaking trucks detect one another using sensors and cameras, and ideally communicate directly amongst themselves, using vehicle-to-vehicle communication. Advanced platooning systems may have *centralized* control platforms, meaning that the lead truck determines the behavior for all trucks in the platoon, before relaying the decisions to them (G. Lee & Jung, 2021). Platoons may also operate in a *decentralized* manner, each truck receiving information only from its nearest neighbor, as was the case in the Swedish platooning study (Alam et al., 2015), and also in the Field Study. In contrast, the Avinor-application is even more centralized, as all trucks received information from a control platform external to all of the trucks. The feasibility of such an approach for open roads remains unclear.

The automated snow clearing operation at Avinor is characterized by 30-40 km/h speeds and 25-meter gaps between the trucks. It is unclear how platoon behavior would be affected by operation at higher speeds and shorter following distances. While the central control platform and the lack of sensors for distance-keeping should result in little latency, this is uncertain. In fact, vehicle actuation at Avinor is routed through aftermarket equipment for individuals with physical disabilities, such that the control platform bypasses the vehicle computer. Hence, from the perspective of the truck itself, it is still being driven by a human. Such intermediary systems may introduce latency. It would be interesting to explore whether the Avinor control platform, with its workaround, would be able to ensure tighter connection on difficult rural roads. It is also an open question whether the system could handle trucks with different mass and engine characteristics, as all of the trucks are currently identical. While it is unclear whether the trucks at Brønnøy Kalk are directly actuated, interviewees from both use-cases stated that acceleration and gear changes were initially abrupt and uncoordinated before they were tuned. The use of an aftermarket system in the Avinor use-case illustrates the difficulty in obtaining access to interface directly with vehicle systems. Stated otherwise, if access was easily obtained, aftermarket systems would be superfluous. Further, if vehicle manufacturers had been able to implement more capable driver assistance systems, the development of such systems by third-party actors would presumably also have been unnecessary. The use of aftermarket systems at Avinor also brings forth parallels to the need for aftermarket sensors to collect data in the Field Study. Hence, this issue of accessing data from proprietary systems is faced even by rather large organizations, such as Avinor, in this case.

Parts of each industrial use-case could still serve as building blocks for automated vehicles at higher SAE levels on open roads. For instance, trucks at Brønnøy Kalk have object detection capabilities, and they have the capacity for self-localization in tunnels. The digital planning tool at Avinor may inform the design of software to plan routes for automated vehicles. However, neither approach is sufficiently flexible for dealing with unforeseen challenges. The Avinor use-case is unable to detect obstacles, and trucks at Brønnøy Kalk are unable to circumvent them. Both applications shut down abruptly, without warning, in case of outages in GNSS positioning or cellular connectivity. While this may be appropriate for enclosed applications, improved reliability and smoother fallback is needed for operation on open roads. Moreover, the trucks in either application do not communicate directly with one another. This may be needed for automated vehicles on open roads, in order to reduce their reliance on central systems. For reliability, a distributed system where trucks act independently would likely be harder to implement, but also more resistant to faults. The enabling technologies behind the two industrial use-cases are simple compared to what will be needed for automated trucks on public roads, Still, development has been difficult. Both interviewees had experienced the systems becoming increasingly complex once they scale, creating dependencies which complicate troubleshooting efforts.

Summary of Enabling Technology

Interviewees in the Stakeholder Study generally believed that the enabling technology for truck platooning is currently not ready for deployment outside of enclosed areas. Hence, they also saw the prospects of higher-level automation on public roads as unlikely in the short to medium term. Instead, they focused mostly on requirements and ideas pertaining to matchmaking systems. Experiences from the Field Study suggests that vehicle-to-vehicle communication is needed to achieve fuel savings from truck platooning, by facilitating the use of shorter and more consistent following distances between the trucks.

For both applications in the Industrial Study, technological simplifications were used which make them difficult to adapt to open roads. To this end, the two interviewees acknowledged that significantly higher levels of reliability are needed for open-road applications than were currently available in their respective use-cases. Communication between the trucks in both use-cases is simplified by having it run through a central node, and both require CPOS base stations, both aspects comprising bottlenecks for deployment at scale. Moreover, open-road applications require capabilities for obstacle detection and avoidance which the use-cases either do not, or only partly possess. Furthermore, the Avinor use-case circumvents the vehicle computer using an external system. As the enabling technology for automated driving matures, the use of such intermediary layers should diminish. Hence, while many of the findings from the Industrial Study were interesting in their own right, their transferability to open-road automation is unclear, owing to the complexity of challenges encountered on open roads.

4.4 Economics

The Stakeholder Study and the Industrial Study provided findings regarding the economic prospects of truck platooning, addressing the following research question:

RQ4: What economic considerations facilitate or hinder deployment of truck platooning on public roads in Norway?

4.4.1 Stakeholder Study

The Stakeholder Study identified several economic matters which affect the implementation of truck platoons. Associated findings and discussion were grouped as follows:

i. *Savings*
ii. *Incentives*
iii. *Route Length*

Savings

Due to regulatory conditions and insufficient technological maturity, interviewees in the Stakeholder Study agreed that all platooning trucks would still be manned in the short term. Hence, initial economic benefits would be related to fuel savings, as opposed to being related to reduced labor costs. Inspired by previous literature, the case examples in the Stakeholder Study, summarized in **Table 6**, assumed flat 5% fuel savings for both trucks in a two-truck platoon. Carriers did not see these savings as sufficient to adopt platooning, stating that other operational decisions, such as small speed restrictions, and optimization of vehicle maintenance, are likely to match or outweigh fuel savings of such magnitude. Hence, stakeholders concluded that the economic gains associated with the removal of drivers in following trucks is likely needed to convince carriers to adopt platooning. This was also implied by one of the participants in the Field Study: "*In the big picture, the fuel saving [are] not the point here*". As a parallel, the savings associated with personnel reductions were also the main driving forces for the two automated operations in the Industrial Study, as stated in Paper 4.

One interviewee in the Stakeholder Study commented that many carriers face costs related to minor accidents which are not properly internalized, proposing that platooning may reduce their frequency. In the current technological and regulatory landscape, however, platooning at short following distances may compromise the safety of occupants (Axelsson, 2017). Hence, most stakeholders believed that the reliability of platooning systems must be proven before savings may be unlocked from foregone accidents.

Incentives

As mentioned in subchapter 2.1.3, interviewees pointed out that the lead truck is necessary for platooning, but, at best, it saves comparably little from partaking in the arrangement. For platoons consisting of trucks from different carriers, the need for matchmaking systems was identified by several interviewees, serving to assign the leader some of the savings to motivate the formation of platoons. Alternatively, scoreboards could be kept, ensuring rotation of positions such that no carrier receives excessive benefits. One of the case examples also elicited responses to the idea of drivers being paid lower wages if they are resting in following trucks while the platoon is moving, as compared to the wage which is paid during solitary, conventional driving. While interviewees unanimously opposed this idea based on labor practices, it does raise the question of how drivers should be incentivized to join platoons.

As discussed in subchapter 2.2.1, the operating margins of Norwegian carriers are under pressure. Hence, interviewees believed that potential economic upsides from platooning must be unlocked by first driving down the technological costs. The three shippers which were interviewed in the Stakeholder Study were interested in ensuring inexpensive, reliable, and environmentally friendly goods consignment. Subject to these objectives, their logistics companies of choice were mostly free to use whatever modalities they pleased. Government incentives were suggested as a means to introduce new technology via shipping agreements, but interviewees believed that any amendment of regulations to favor truck platooning is still premature.

Regarding driving time regulations, one NPRA interviewee stated that a prospective increase from 4.5 to 6-hour daily driving periods would be economically favorable for carriers, as it would facilitate conventional operation between many Norwegian destinations which are currently just out of reach in one day of driving. Irrespective of automation, some interviewees pointed out that hourly wages may increase if transit time is reduced. If shipments reach their destination on the same day, transportation costs may not have to cover wages associated with overnight rest. This proposition could constitute a win-win situation with higher earnings for carriers, as the prices shippers pay for the service may not have to come down equally far. Alongside price cuts for shippers, part of the earnings may be redistributed to the drivers.

Route Length

The economics of truck platooning depend strongly on the duration of the platooning period. The case examples in the Stakeholder Study revealed that carriers would hardly consider platooning for routes that are shorter than 100 kilometers. Short routes are also unlikely to justify waiting for a partner. Interviewees mostly agreed that the longer the distance which platoon driving comprises of the total trip length, the more profitable it will be. A carrier representative conjectured that for shipments exceeding 400 kilometers, truck platooning might be preferred over freight trains.

An interviewee from a research institute suggested that discussions of costs and savings from platooning should be generalized from specific case examples and into a five-part framework, including route length (i), speed (ii), driving duration (iii), number of vehicles in the platoon (iv), and the number of people involved (v). While this has been done in previous literature on truck platooning, e.g., Boysen et al., (2018) and Noruzoliaee et al., (2021) such modelling could be performed using Norwegian road freight characteristics, to study which shipments may be feasible, and the extent of the corresponding savings.

4.4.2 Industrial Study

The Industrial Study provided valuable information pertaining to the costs and savings associated with introducing automated trucks on industrial sites. For instance, the use-case at Brønnøy Kalk hinted at the trade-off between the economics associated with ensuring appropriate on-site infrastructure maintenance, versus ensuring technological robustness in on-board systems. This again supports the postulate that automation may tighten the link between vehicles, infrastructure and digital systems (OECD Publishing, 2023, p. 8). Moreover, both use-cases suggested that automation may provide benefits for conditions and safety of workers, with second-order economic effects. However, the most important findings and discussion from the Industrial Study were related to the following topics:

i. *Flexibility*

ii. *Closed Areas and Proactive Initiators*

Flexibility

The main economic driving force in the Industrial Study relates to the potential for cost savings from unmanned operation, making the use-cases more flexible. Specifically, the two industrial use-cases faced similar concerns in terms of ensuring flexibility for ramping up and down operations in response to customer demands. Several carriers in the Stakeholder Study reiterated this notion, stating that external demands often were difficult to forecast, and that significant coordination was required to meet orders. As is the case for Brønnøy Kalk, carriers are profit-driven actors. While Avinor is a state-owned company, it is interested in minimizing its costs, making it subject to similar objectives. Hence, economic savings for carriers will likely constitute the main driving force for truck platooning, and deployment with manned followers seems unlikely. Once systems emerge which allow for driverless followers, carriers may be swift adopters.

Closed Areas and Proactive Initiators

The interviewees from the two industrial use-cases remarked on the investment costs for developing automation, alongside the cost related to system outages. Closed areas again emerged as enablers, particularly for Brønnøy Kalk, as economic losses from downtime were contained. Another economic enabler relates to the involvement of at least one actor being willing to incur significant development costs. Both use-cases had this in place, but they differed in regard to which of the actors had done so. At Brønnøy Kalk, the provider of the transport solution had taken on expenses, in exchange for retaining the mining company as a client once the system becomes operational. At Avinor, the infrastructure owner had itself funded the development work. Due to the large number of stakeholders involved in road freight, such consortia are likely to involve many different companies with specialized knowledge and equipment, and the costs will be many orders of magnitude higher.

Summary of Economics

Truck platoons are likely to remain manned in the short term. However, the business-case behind platooning in Norway seems to hinge upon the removal of drivers. This was suggested both by interviewees in the Stakeholder Study and in the Industrial Study. If the technology improves, regulators may eventually allow for driverless operations, but costs related to procuring such technology will likely remain high in initial stages of deployment. Well-funded companies or infrastructure providers may be needed to spearhead the required developments. Government incentives could be considered to expedite adoption, but still, as discussed in the organizational theme, truck platooning would likely only be feasible on long trips which justify waiting for a partner.

5 Limitations and Reflections

The large scope, and the methodological diversity embodied by the three case studies, comprise key strengths of this work. However, since the case studies did not meaningfully overlap, they would all benefit from external validation. This chapter reflects on other limitations to the current work, including methodological limitations of each case study, and the quality and validity of the results which were produced. Suggestions for future work are also provided. First and foremost, this chapter remarks on the structure of the thesis.

5.1 Structure

The thesis covers four broad and related themes of truck platooning, shown in **Figure 1**, using three separate case studies. The work also spans different automation levels, and many levels of detail, as illustrated in **Figure 5**. In particular, the Industrial Study introduced new concepts which widened the scope of work. While the themes were still relevant for the Industrial Study, the research questions were less so. The research questions were considered anyway, for all three case studies, with frequent explanations that the Industrial Study aimed to provide reflections into higher automation levels. While only partially related to truck platooning, the Industrial Study illustrated issues which may be encountered in a future road system populated by automated trucks. Hence, based on an overall assessment, its inclusion was considered worthwhile.

5.2 Stakeholder Study

Broadly speaking, limitations for the Stakeholder Study relate to the design of case examples, and to the availability of knowledgeable informants within the field of vehicle automation.

With respect to the case examples, which were introduced in **Table 6**, interviewees suggested that they should have been designed with more variation regarding road conditions, lengths of shipments, and waiting times. For instance, case example 1 revolved around a very short route, making it a poor candidate for platooning. Similarly, in case example 4, the post-wait portion of the drive was short and the savings small, perhaps unrealistically so, with respect to justifying the wait which was needed to form the platoon. Moreover, interviewees were not presented with case examples of shipments which crossed national borders. While this was intentional, serving to narrow the scope, a large part of Norwegian road freight volumes do traverse national borders, and such shipments should be considered in future work.

Regarding the availability of informants, it would be beneficial to have recruited more interviewees with expertise pertaining to automated driving systems. The representative from the truck manufacturer being the only one, comprises a limitation. It may also be argued that the total number of participants should have been higher. As stated in subchapter 3.2.1, however, recruitment of new participants was concluded once incremental interviews started providing fewer novel insights. All things considered, the number of participants seemed sufficient, and the Stakeholder Study was considered a success. To this effect, Paper 1 provided input for several subsequent endeavors. For example, it was cited repeatedly in a review paper summarizing research efforts pertaining to truck platooning (Mahajan et al., 2024).

5.3 Field Study

The methodological limitations of the Field Study were categorized in the following topics:

i. *Planning*
ii. *Baseline and Repetition*
iii. *Platooning Duration*
iv. *Radar and Video*
v. *Data Analysis*

5.3.1 Planning

Subject to a short-lived relief in the covid-19 pandemic, the preparation period for the Field Study was short. Dialogue with the foreign carrier was needed to clarify what data would be provided, and what data had to be collected. However, coordination was difficult, and key clarifications came late, providing little time for procurement of instrumentation, preparation, and for developing and testing frameworks for data analysis. However, applied research is known to be subject to constraints (Guest et al., 2013, p. 8) such as time and resources, and also contingent on the operating characteristics of the industry in which it is conducted. Given these difficult circumstances, the planning and coordination which took place did succeed in producing useful results and reflections.

5.3.2 Baseline and Repetition

The Field Study did not obtain a baseline of manual driving. Ideally, the three trucks should have performed the same drive, without using the platooning system, sufficiently far apart from one another, such that they had operated independently. Both such a baseline test, *and* the test where the platooning system is active, should be repeated multiple times, as also suggested by others (e.g., Alam et al., 2015; Barnard et al., 2016). Further, the 13.5 metric ton weight difference for truck 3 versus trucks 1 and 2, affected the platoon in the Field Study, and hence also the behavior of the three drivers. However, lacking a baseline test, it is unclear which of the observed effects stem from the platooning system, the road infrastructure, or from driver behavior. To this effect, the number of participants in the trial should ideally also have been higher. For instance, other field studies of truck platooning in the human factors realm have included as many as 10 participants (Castritius et al., 2020). Naturally, this would provide more generalizable results, but it would also expand the scope of work beyond the means which were available. In comparison, the Swedish tests had mass differences of approximately one metric ton (Alam et al., 2015). At the same time, since real-life platooning may involve weight differences, the Field Study showcased a realistic scenario. It could also be argued that the weight difference made it hard to quantify the fuel savings from platooning, as only the middle truck amongst the two followers provided useful data for comparison against the leader, given that only these two trucks had equal masses. Still, fuel savings were small or nonexistent, due to the large inter-vehicle distances which were used in the study, which arguably comprise another limitation in their own right.

5.3.3 Platooning Duration

Since the two ACC systems worked differently subject to the presence of a preceding truck, it would have been ideal to study only the driving periods where the chain link was active, meaning a preceding truck was detected. As discussed in subchapter 3.3.5, efforts to film the instrument cluster were unsuccessful. Hence, access to the exact engagement status of the two longitudinal automation systems was not available. Instead, cameras in the pedal bay were used to discern whether longitudinal control was being performed by the driver or by the vehicle system. However, this footage could not be used to distinguish the two longitudinal ACC systems from one another. As a consequence, video analysis had to be based on the total driving time with longitudinal automation active, also including driving periods where the trucks were further apart than what is traditionally considered *platooning*. However, dialogue in the two following trucks revealed that the chain link mostly remained active on high-standard roads. Hence, driving periods without the chain link may have likely yielded more interesting results. The inclusion of all periods with longitudinal automation served to maximize the data collection before it was narrowed down using coded videos.

5.3.4 Radar and Video

Radar sensors were used for collecting inter-vehicle distance data. The data was filtered using videos from the driving scene, alongside metrics obtained from the radar sensors. While all trucks were identically instrumented, only data from the two trucks that mostly served as followers were used. Paper 2 describes the methodology. The efforts were successful, and the conclusions were somewhat validated by the similarities observed from both sensors. The study would benefit from being repeated, but this was beyond the scope of the current work. For instance, established radar sensors with known operational features could be used simultaneously to establish a baseline for comparison. Ideally, experiments with the sensors should have been systematic and controlled, to identify the most appropriate configurations of mounting and radar parameters. Finally, testing truck platooning *and* a new sensor system simultaneously, complicated the process of discerning which findings in the radar data stemmed from sensor-related methodology, and which were introduced by the platooning set-up. However, subject to the constraints in planning and execution, performing separate trials was outside the scope of work.

Filming and video coding established a rich dataset. Unfortunately, it was not utilized to its full potential. The original goal was to digitally recreate the drive to enable integrated analyses of videos, radar data and driver communication. While the work by Vindenes (2022) showcases these efforts, a useful level of integration was not achieved. Moreover, the effort which was exerted to curate the dataset of conversations between participants based on audio streams from the cameras, was large compared to the number of useful statements. Nevertheless, the video codes were paramount for Paper 2, and they expedited the writing of Paper 3, for which the participant conversations also became important.

5.3.5 Data Analysis

Following the Field Study, significant efforts were exerted in curating and analyzing data. As briefly described in **Table 8**, some of the data were of dubious quality and were eventually discarded, as subsequent analyses turned out to be unsuccessful. Considerable effort was exerted to code videos, curate radar data, transcribe and code communication, and extract and interpret data from the fleet management system. Regarding the latter, such systems should ideally log at higher frequencies, to enable analyses of specific driving situations, as opposed to motivating only general remarks over longer driving periods. Future studies should consider involving data scientists in designing the data collection strategy, as this is likely to streamline later analysis efforts.

5.4 Industrial Study

While the Industrial Study was limited by the small number of use-cases, no more were available in Norway, and efforts to contact potential use-cases elsewhere were unsuccessful within the time frame. However, the study was strengthened by the inclusion of two use-cases, as opposed to only one, facilitating comparisons between them. Further, the Industrial Study did collect opinions of informants with experiences from testing and implementation of automated driving systems, addressing one of the main limitations in the Stakeholder Study. Another limitation of the Industrial Study may relate to its descriptive nature, but since little information was available regarding either use-case, this is to be expected.

The Industrial Study may be criticized for not interviewing more than two representatives from each use-case. This would have strengthened the findings, and it would likely have provided more in-depth learnings for each theme. However, sufficient information was gathered from the two interviewees which were available, such that all themes within the scope of the study were adequately covered.

6 Conclusions

This chapter first reflects upon the contributions of the current work, before it details key insights for each of the four main themes, and provides recommendations for future actions.

6.1 Contributions to Scientific Knowledge

The present thesis represents a contribution to the body of research on truck platooning by investigating different framework conditions from those which have typically been the subject of scientific study. Focusing on the country of Norway, the thesis provides an overview of the local characteristics which enable or prevent the operation of truck platoons. This pertains particularly to the prevalence of two-way, two-lane rural roads, and to the tendency for goods-producing industry to be located along such roads, which are often characterized by sparse volumes of trucks. The research is useful for Norwegian policymakers since most Norway-specific reporting on vehicle automation have overlooked road freight (e.g., COWI, 2019; Nenseth et al., 2019). Moreover, previous testing of truck platooning undertaken in Norway (e.g., Norwegian Public Roads Administration, 2018a, 2018b) have not culminated in openly available data which can inform future research efforts. Furthermore, the work is useful for international readers, as it provides insights on truck platooning in an environment where it has not been considered before. Readers can learn from the experiences which were made, and many of these are relevant for other countries with similar characteristics. The current work is unusually interdisciplinary, containing both technological and social-scientific parts, making it a holistic contribution to previous work.

Firstly, the current work represents the first time where Norwegian stakeholders in the road freight sector were systematically interviewed to uncover their viewpoints towards truck platooning. Several country-specific whitepapers exist regarding truck platooning, the closest ones being from Sweden (Axelsson et al., 2020; Kammer, 2013) and Finland (Siren, 2021). Nearly unanimously, however, these publications consider platooning on motorways. The current work identified opportunities and barriers towards truck platooning which are more specific to the Norwegian situation, such that it may better inform future policy. While the Norwegian context is novel, and a handful of novel deployment ideas materialized, most results are quite general, and they mirror findings from similar studies conducted in other countries. Some examples include targeting high-volume freight types with high regularity, and using ferry terminals as starting points for platoon coordination.

Secondly, the current work constitutes the first time where truck platooning was scientifically tested on open, public roads in Norway, using a formalized data collection strategy. In short, and in alignment with previous research efforts, high-standard roads seem most feasible for deployment (e.g., Turri et al., 2017). Do note that the corresponding findings from the current work are based on a rather rudimentary platooning system *without* communication between the trucks. Previous research suggests that such communication may yield more favorable results (e.g., P. Singh et al., 2018). Still, the testing which was undertaken is useful, as it contains many practical observations from truck platooning in conditions which are outside of the ODDs of trials undertaken elsewhere, including narrow tunnels, sharp curves, steep gradients and even short segments of slippery winter conditions.

Thirdly, the current work established a creative methodology with inexpensive aftermarket equipment for collecting inter-vehicle distance data during truck platooning. This was done since such data from in-vehicle systems were unavailable. This is likely to be of value for practitioners when conducting future field trials. The truck platooning application represents a novel use-case for the specific type of radar sensor which was used. Hence, the detailed descriptions of this methodology adds significantly to the scientific best-practices for the use of this sensor type. Furthermore, its outputs were used to underline the practical observations which materialized from the platooning trial. For instance, it showed that narrow tunnels are associated with shorter following distances, indicating that such tunnels comprise bottlenecks for truck platoons.

Fourthly, the current work adds to the scientific knowledge by providing novel insights into two applications of automated trucks at high automation levels at industrial sites. The motivation for doing so, was to explore how implementation-related challenges had been solved in geographical areas where the ODDs were presumed to be simpler than what they are on open roads. Experiences from such applications may hint towards the complexity of automating road freight on public roads. With reference to the literature on automated driving, the premise of knowledge-transfer across these different domains is somewhat unusual, which is also partly why it adds value to the scientific body of work. The two specific industrial applications have not previously been studied in this context, and only limited information about them was publicly available prior to the work being undertaken. The main take-away relates to the benefits of constrained areas for testing and development of automated driving systems. These benefits, however, seem to be difficult to transfer to public roads.

6.2 Key Insights

6.2.1 Conventional Infrastructure

ACC-based truck platoons at SAE level 1 appear to struggle with retaining string stability on steep uphill and downhills sections, and in sharp horizontal curves on rural roads. Tight tunnels and winter conditions are also problematic. On the other hand, flat and fairly straight routes provide good conditions for platooning. These findings suggest that truck platooning is most viable on motorways, in line with recommendations from research conducted in other countries. However, the road network in Norway consists mostly of two-lane, two-way roads, with few motorways. If motorways are required for truck platooning, carriers may be limited to platoon along a limited network of suitable routes, which reduces its viability.

However, this research suggests that other road types may be suited for truck platooning. For instance, alternating three-lane expressways may facilitate platooning, while being preferable over constructing motorways, in light of rising environmental concerns. Such roads should provide better conditions for platooning and general vehicle automation than what typical rural two-lane roads do. Some two-lane roads may also be applicable for platooning, particularly those which are void of difficult bottlenecks. The removal of bottlenecks will likely help make rural roads platoonable and automation-ready. In this respect, routes with large freight volumes should be prioritized, since facilitating automation at large scale using conventional means will be prohibitively expensive. To incentivize road improvements, the value of cargo which traverses freight corridors could be accounted for in planning decisions. However, vehicle manufacturers and technology companies should certainly continue developing their automation systems and not rely on roads authorities to upgrade their roads. For the coordination of truck platoons, however, roads authorities should be encouraged to implement relatively simple elements such as stop pockets and truck stops at frequent intervals.

The work identified several infrastructural modifications for automation in industrial areas, but few of them are applicable for open roads. Most importantly, simple infrastructure is an enabler for automated applications. Regarding road maintenance, the industrial use-cases suggest that automation may link together the vehicles, the road, and digital back-end systems, making the road freight system more complex and interdependent. Hence, as technological systems for truck platooning and automated driving improve over time, continuous research is needed to understand what types of modifications to conventional road infrastructure may be considered worthwhile.

6.2.2 Organization

Truck platooning will require a mindset shift among Norwegian carriers, as competing firms must work together to obtain sufficient truck volumes. Some rural freight routes in Norway were shown to have truck volumes which are sufficient to enable platooning. Still, trucks may have to wait for one another, and matchmaking is a largely unresolved issue, complicated by short planning horizons. The production facilities of shippers, and the typical road standards on county roads, call for organizing truck platoons along higher-volume routes instead. Organization of platoons may benefit from the fact that the Norwegian road network provides few routing options. Truck platooning may also benefit from the high asset turnover among Norwegian carriers, as this may expedite the deployment of platooning technology, when it becomes available.

Findings from industrial applications of automated trucks reveal that central oversight, and the decoupling of automated operations from irregular activities, are clear organizational enablers for automation. In closed areas, shortcomings related to technology or infrastructure may be overcome using organizational means which are hard to transfer to public roads. This is in part due to the organizational landscape. On public roads, more actors are involved, the risk for unexpected situations is higher, and the operational environment is more diverse and complex. In this regard, significant work is also needed to ensure that humans and automated vehicles can safely co-exist. Manned truck platoons are simpler in this regard, owing to the presence of at least one accompanying human for driving and supervision.

6.2.3 Enabling Technology

Truck platooning is regarded as a technologically simpler way to achieve automation on open roads, versus free-agent automation. However, current truck platooning systems do not seem to be sufficiently mature to warrant deployment. Current operation of ACC-based SAE level 1 systems requires the presence of drivers in all trucks, to handle lateral automation. Since the trucks need drivers, platooning may be constrained by their safety and comfort. Hence, distance settings for such systems are too large to yield fuel savings. The systems also seem to poorly account for weight differences between partaking trucks. Wireless communication between the trucks may solve some of these issues. Moreover, electric trucks would likely overcome some of the barriers related to uncoordinated driving on rural roads, such that these two technologies in combination should be tested. In addition to the driving automation systems, software is needed to help trucks to convene for the purpose of platooning. While the requirements for such systems are mostly known, the software needs to be made or adapted.

While industrial use-cases of automated trucks are state-of-the-art, they are simple compared to systems needed on open roads. The operational conditions enable what may essentially be described as *technological shortcuts*, referring to the use of organizational and infrastructural means which would be impractical or infeasible to implement on open roads. These means work well on closed areas, but they provide insufficient flexibility and reliability versus what would be needed for reliable automation on open roads. Difficulties also remain in setting requirements for the removal of safety drivers in platoons. This may suggest that it will take time to achieve sufficient reliability for the operation of both platooning systems with driverless followers, and free-agent trucks.

6.2.4 Economics

This work suggests that truck platooning on Norwegian roads may not yield notable fuel savings, especially if distances between trucks remain large. Carriers may instead wish to implement simple and cheap measures, such as speed restrictions and optimized maintenance procedures. The existence of a positive business case, both on societal level, and for individual carriers, is important for the proliferation of truck platooning. However, the business-case for truck platooning in Norway seems to hinge upon the removal of drivers, which warrants higher automation levels and greater reliability than currently seems to be available in on-road truck platooning systems.

Distribution of savings from truck platooning operations is largely unsolved, but this could be implemented in coordination software. Incentives from the public sector may also be used to facilitate carriers and drivers to partake in platoons, and incentives could be used to reward shippers who enter into agreements with carriers who support and engage in platooning operations. If the concept lives up to its potential, truck platooning may become cheaper than alternative modes, such that road freight captures additional market share.

6.3 Recommendations

To enable truck platooning and automated driving most effectively, research and development efforts must continue. While challenges remain regarding all four of the main themes, the extent to which the underlying technology is sufficiently mature, emerges as the most pressing question. A useful next step would be to perform platooning field trials using wireless communication, as such systems do exist. This would enable short following distances, potentially solving some of the operational challenges which were identified related to truck platooning on rural roads. Carriers involved in future testing should ideally be domestic and based in close proximity to the research team, to facilitate coordination. Alternatively, truck manufacturers should be directly involved in piloting initiatives, with formalized agreements, to streamline data collection. Experts in instrumentation could also be involved, to ease data analysis efforts.

Truck platooning should be tested on more road types, including alternating three-lane expressways. Prospects of using ferry terminals and customs stations for platoon coordination should also be explored further. In this regard, the waiting time variability of main freight corridors should be studied, and shipments and routes which traverse national borders should be included in future work. Truck platooning and automated driving in Norway are associated with many challenges. Arenas could be established where industry can collaborate to safely identify and understand the problems, and explore the opportunities which can arise from various facets of automated trucking.

While truck platooning may not yet be sufficiently mature to warrant deployment, roads authorities should study the technology at frequent intervals, testing and familiarizing themselves with the latest developments. Road freight volumes in Norway are forecast to rise over the coming decades, and truck platooning may eventually prove itself as a useful operational concept to support the growth of the sector while limiting its negative externalities. Ideally, we should strive to deploy technological solutions which play to our local strengths, and which harmonize with the Norwegian road standard and industrial structure. More research is needed to understand whether this is the case for truck platooning.

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Paper 1

Eitrheim, Maren Helene Rø; **Log, Markus Metallinos**; Tørset, Trude; Levin, Tomas; Pitera, Kelly. (2022). *Opportunities and Barriers for Truck Platooning on Norwegian Rural Freight Routes*. Transportation Research Record. Volume 2676 (6).

Opportunities and Barriers for Truck Platooning on Norwegian Rural Freight Routes

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ABSTRACT

Truck platooning can potentially make road freight transportation safer and greener. Technological readiness, business opportunities and acceptance of truck platooning have mainly been studied for multi-lane highways with ample truck volumes. Less is known about truck platooning in areas with low traffic volumes, challenging roads and weather conditions. This paper investigates opportunities and barriers for truck platooning on Norwegian rural freight routes through stakeholder interviews and realistic case examples. Given modest freight volumes, dispersed industry clusters and challenging road conditions, this study identifies several prerequisites to deploy platooning and achieve economic savings. The paper discusses future steps to organize platooning across carriers, ensure appropriate infrastructure and gain acceptance among truck drivers, motorists and other road users.

Keywords: truck platooning, wireless truck convoys, rural freight routes, stakeholders, two-lane roads, road freight, public acceptance, driver workload

INTRODUCTION

Truck platoons are convoys of virtually linked trucks that travel together with small headway distances *(1)*. As such, platoons consist of one lead truck, and one or more following trucks, driving closely behind each other as a train on the road. Truck platooning is forecast as one of the earliest applications of road vehicle automation to become commercially viable *(2)*. The operation of platooning trucks can be structured along the Society of Automotive Engineers (SAE) levels of automation (3), based on the allocation of tasks between a human driver and the driving automation system. The levels range from No Driving Automation (level 0), in which the *human* performs all driving tasks, to Full Driving Automation (level 5), where the *system* performs all driving tasks without requiring human intervention. In intermediate levels, the human driver and automated system share vehicle control. This paper assumes that a human driver is present in the first truck, having operational control of the platoon. The presence and role of drivers in following trucks depend on the level of automation and the state of cooperative technology. Additionally, platooning can be classified based on use-cases ranging from restricted areas, dedicated lanes or roads, to entire public road networks. This is often referred to as the operational design domain (ODD), denoting environmental and roadway conditions under which an automated driving system is designed to function *(3)*. Furthermore, platooning can be deployed within a single carrier, organized across carriers, with trucks of the same or different manufacturers. The term platooning is also used in the context of passenger vehicles, although the truck application dominates *(4)*. In this study, *platooning* refers specifically to *truck platooning* using heavy goods vehicles.

The expected benefits of truck platooning include fuel savings, reduced emissions, increased operational efficiency, and improved safety. Shorter gaps between trucks reduce aerodynamic drag, lowering fuel consumption 5-15%, depending on headway distance, mass, and other vehicle configurations (*1, 2, 5)*. Platooning may increase traffic throughput by reducing inter-vehicle spacing, freeing up capacity for other motorists, and by homogenizing or smoothing out arterial speeds *(6)*. Platooning may thus reduce infrastructure investments for accommodating predicted traffic volume increases *(7)*. Platooning-related hazards are cut-in situations, as well as the risk of following truck(s) running into the preceding vehicle. As long as platoons are manned, issues also exist relating to driver workload and possible decreases in situation awareness for following drivers while monitoring automated systems *(4)*. Poor rest quality, underload effects, and sustained time-on-task due to longer monitoring periods may cause fatigue and reduced performance *(4, 8)*. Sensors, communication, and centralized traffic control may mitigate these risks *(4)*. When fully automated, platooning is expected to enhance safety by reducing reaction times, human errors, and the frequency of rear-end collisions *(9)*.

Platooning has been tested and evaluated on ideal conditions elsewhere, with promising results *(e.g., 10, 11, 12, 13)*. Furthermore, acceptance studies have been performed for platooning on multi-lane highways *(e.g., 14, 15)*. Opportunities and barriers for platooning have also been investigated from a business-case and organizational perspective *(e.g., 16, 17)*. Due to dispersed industry clusters, adverse weather, low road standard and small traffic volumes, previous findings are not directly transferrable to Norway *(18)*. This study investigates prerequisites for introducing platooning on Norwegian rural freight routes, identifying opportunities and barriers expected by involved stakeholders. Local road conditions, regulations, freight volumes and stakeholders are outlined below.

THE NORWEGIAN CONTEXT

The Norwegian public road network is classified into national, county, and municipal roads, organized under the jurisdiction of three different public agencies. While national roads are owned and operated by the Norwegian Public Roads Administration (NPRA), county and municipality administrations are responsible for the two latter categories, respectively. Due to scarce population and difficult topography, motorways make up 1% of the primary and secondary road network, while making up 1-12% for most European countries *(19)*. Norwegian motorway density is also generally lower than for the other Nordic countries *(20)*. The Norwegian road network is mostly comprised of two-lane roads, many of which are demanding with respect to curvature, road width and roughness, with sparse use of medians and rumble strips, necessitating low speed limits (*21*). Furthermore, Norway has numerous tunnels and ferry connections, traversing mountains and fjords, compared to most other countries.

Norwegian regulations allow for the general use of heavy goods vehicles with a maximum length of 19.5 meters and an upper weight threshold of 50 metric tons. The current paper studies platooning considering vehicles in this category. The NPRA is gradually allowing for longer and heavier configurations on qualified roads. Specifically, the European Modular System (EMS) refers to configurations of tractors, trailers and trolleys restricted to a total length of 25.25 meters and 60 metric tons.

To reduce fatigue among truck drivers, hours-of-service regulations have existed for many years in developed countries. Although variations exist between countries, such regulations focus on limiting maximum hours on duty during a 24-hour period and regulating breaks during the workday and between work periods. In Norway, truck drivers are required to comply with European rules *(22)*: Essentially, daily driving periods shall not exceed 9 hours, with a break of 45 minutes after maximum 4 ½ hours of driving. Daily overnight rest periods must be at least 11 hours. Total daily on-duty time, including driving and non-driving tasks, cannot exceed 13 hours.

The presence and role of drivers in the lead and following trucks may change in the future, enabling new business opportunities and ways to organize road freight. In the future, only lead trucks may require attentive drivers, allowing rest or administrative work to take place in following trucks while moving. The order of trucks could be switched to utilize driving time for each driver, facilitating around-the-clock operation. This would require amendments to the regulations to allow currently forbidden in-vehicle overnight rest while moving. When only the lead truck is manned, while followers are unmanned, platooning could alleviate the worldwide shortage of professional truck drivers *(2).* Eventually, lead vehicles may also become driverless. The Norwegian Truck Owners Association estimates that 10 000 new drivers are needed over the next 8-10 years for its member carriers to retain current market share *(23).* This shortage stems from a growth in transport demand, the current workforce aging, and low recruitment.

Norwegian industry clusters, with export-oriented businesses such as petroleum and fish farms, are dispersed along the coastline. Many road freight shipments start or end at facilities located along rural roads. Frequently, goods are transported from rural industry sites to the Oslo capital district for domestic distribution and export. Similarly, most of the imported goods arrive at terminals in the capital district and are distributed to consumers country-wide. Shippers and receivers depend on the ubiquity and flexibility of road freight, connecting rural and urban areas. The total Norwegian freight demand is expected to increase from 530 to 760 million tons in 2050, with minor changes in modal shares for road (53 to 55%), sea (40 to 37%) and rail freight (8%, unchanged). Thus, volumes are forecast to increase by 50% for both road and rail freight, and by 33% for sea freight (*18*). For many years, however, the Norwegian government has set national policy objectives to shift modal distributions away from road, towards rail and sea. As such, current forecasts do not support these political goals.

Figure 1 shows main stakeholders and their roles in the road freight transport system. Carriers are presumably the main direct beneficiaries of platooning, saving fuel and personnel costs, and possibly reducing future staffing requirements. 42% of Norwegian carriers are owner-operators, 48% operate 2-10 trucks, while the remaining 10% operate more than 10 trucks (*24*). The dominance of smaller carriers suggests between-carrier cooperation to make platooning viable. Platooning may also improve shipper competitiveness by delivery cost reductions and by increasing their ability to maintain production in rural regions. These cost reductions may also benefit receivers through lower pricing. While also being a national road owner, the NPRA acts as an authority across all road categories, having several roles and responsibilities for ensuring a safe, efficient, and environmentally friendly road system for all road users. Residents, workers, tourists, and others may encounter platoons on the road, and may also benefit from infrastructure changes needed to accommodate them. Although their involvement in the road freight transport system is indirect (*25*) their interests should be considered, as public acceptance and willingness to cooperate with platoons is a prerequisite for deployment (*26, 27*). Policymakers aim to make regions attractive to businesses and residents, while balancing private and public interests (*28)*. They may also need to decide on frameworks for permitted platooning technologies, and regulate aspects such as allowed weight, number, and distance between trucks. Moreover, authorities and policymakers should decide on licensing requirements and trucking regulations, as well as on which roads platooning could be permitted. Original equipment manufacturers (OEMs) should clarify capabilities and limitations of installed technologies, their ODDs and requirements for monitoring and manual intervention. This impacts the legislation and infrastructure requirements for enabling platooning.

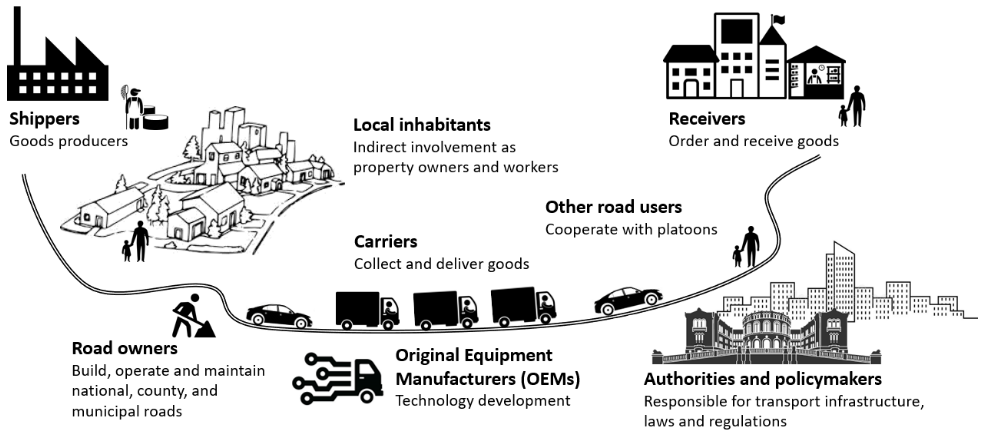

Figure 1: Main stakeholders in the road freight transport system.

METHODS

This study identifies opportunities and barriers for platooning in Norway through semi-structured stakeholder interviews *(28, 30)*. Realistic case examples were used to facilitate discussions of business opportunities, acceptance, organizational means, and the level of infrastructure readiness needed to accommodate platooning on rural freight routes.

Stakeholder interviews

Purposive and snowball sampling techniques were used to recruit 21 interviewees, 4 women and 17 men, based on their knowledge about either or both freight transport and Norwegian road infrastructure. Some were also familiar with vehicle automation technologies. They represented carriers (n=4), shippers (n=4), researchers (n=4), the NPRA (n=3), county administrations (n=2), interest organizations (n=2), railway terminal owners (n=1), and OEMs (n=1). Shippers included a seafood corporation, a furniture manufacturer, and a natural gas distributor. Two interviews included two participants from the same company. The other interviews were conducted with participants individually. 7 interviewees were former truck drivers. To some degree, shippers may also be considered representing receivers, as they order and receive raw materials for production.

Informed consent was collected from all participants, and 90-minute semi-structured interviews were conducted during spring 2021. The interviewee information letter included a short explanation of platooning and examples of questions from the interview guide. Participants introduced themselves at the start of the interviews, immediately after which they were asked about their understanding of platooning. Subsequently, the authors reiterated the explanation provided in the information letter, to ensure common terminology. The interview guide included open-ended questions that allowed for subjective reflections and discussions about platooning in Norway. Participants were encouraged to speak freely about their experiences and insights relevant for platooning and freight transport, a suitable approach when exploring a topic for which there is limited knowledge *(28, 30)*. Interviews focused on expected opportunities and barriers for platooning in Norway, concerning economic benefits, infrastructure readiness, organizational and regulatory demands, acceptance, and road user safety. Shippers and carriers were also asked about their logistics organization, freight volumes and routes. All but two interviews included case-examples, described below, to facilitate discussions about platooning viability in Norway.

Interviews were conducted digitally, in Norwegian, and recorded for verbatim transcription. Transcriptions were anonymized, coded, and thematically analyzed in the software NVivo 12 (*31*). A combined deductive and inductive approach was used to identify 31 codes and distinct code definitions. The first and second author coded a subset of the data independently. Once a reliable coding scheme was agreed upon, the first author coded the remaining data. Codes were sorted and grouped into higher-order themes as presented in the results and discussion chapter. Interviewee quotations throughout the paper have been translated to English.

Case examples

Five realistic examples were presented during all but two interviews to contextualize the discussion. The cases facilitated discussion of economic savings, freight volumes and infrastructure readiness for platooning. Based on three different routes, the cases reflected rural and coastal challenges, particularly related to the idea of using ferry terminals as starting points for platooning. Once potential routes were found, average hourly traffic volumes were inspected to determine the extent to which platooning would be feasible. Truck traffic volumes were obtained through NPRA inductor loops and the National Ferry Database from 2019. As truck volumes are expected to increase, cases represent conservative estimates for platooning viability. The case examples considered only two-truck platoons. Cases were defined with GPS-coordinates for logistics terminals as start- and endpoints. Subsequently, the SINTEF Energy Module *(32)* was used to calculate route length, fuel consumption and trip duration for conventional, solitary truck driving. As opposed to using fuel savings upwards of 10%, as suggested by (*1,2,5),* savings were based on conservative 5% reductions of fuel consumption from the calculated SINTEF baseline. This is assumed to capture the effects of disadvantageous Norwegian topography and conservative following distances, potentially required for traffic safety. All cases assumed that all platooning trucks are manned by a driver. Cases are described below and visualized in Figure 2 with respect to trip dispositions and geographical locations. As they were part of the interviews, case discussions were also transcribed verbatim and thematically coded in NVivo 12. Findings from case discussions were generalized and included in appropriate subchapters of the results and discussion.

Case 1: Short route, 84.8 km

A transport traverses a busy West-coast ferry connection. All daytime departures have at least two trucks. Terminals in Stavanger and Haugesund represent origin and destination for truck A. Truck B has the same destination. Trucks drive separately to the ferry, convene and platoon after disembarking. Thus, case 1 facilitated discussion on fuel savings for short routes.

Case 2A: Medium route, 280.7 km – 20% lower follower costs

A transport traverses a ferry connection in Northern Norway, where almost all departures include two trucks. Terminals in Narvik and Bodø, respectively, represent origin and destination for truck A. Truck B has the same destination. Trucks drive separately until the ferry, convene and platoon after disembarking. For the discussion, 20% reduced follower costs were proposed, under assumption that the driver partially rests during platooning. Route 2A is longer than route 1, yielding larger absolute fuel savings.

Case 2B: Medium route, 280.7 km – Linking and dissolving at hubs

Based on the same route as case 2A, trucks A and B platoon together between the ferry quay and a hub at which they disassemble and continue manually along different routes. The case introduced participants to the idea of linking and dissolving platoons at hubs.

Case 2C: Medium route, 280.7 km – Waiting for partner at hub
Based on case 2B, the platoon is dissolved at the hub. At daytime, the downstream stretch towards the destination of truck A, is traversed by 6 trucks per hour, on average. Thus, the follower waits 10 labor-minutes for a new partner. Waiting inconvenience, waiting effects on hours-of-service regulations, and value loss of onboard cargo were also discussed.

Case 3: Long route – 722.2 km – In-vehicle rest while moving
This case shows effects of alternating lead driver, while the driver in the following truck rests. The case presumes that “follower time” does not count towards daily allowed driving time but counts as working time. Two trucks start platooning at the hub, destined for an 11-hour drive to Alta. The hub represents the northernmost point of Norwegian rail service. As such, this case exemplifies using platooning as an extension to the public railway system. For simplicity, ferry time is assumed to count towards driving time, and resting drivers are paid driving wage. Truck-and-driver combinations switch at suitable locations when approaching their 4.5-hour driving periods, avoiding overnight rest, halving transit time from 23 hours to 11. Total labor-hours drops slightly, as 11 wage-hours for two drivers, totals 22. Shortened transit time was not assigned any value.

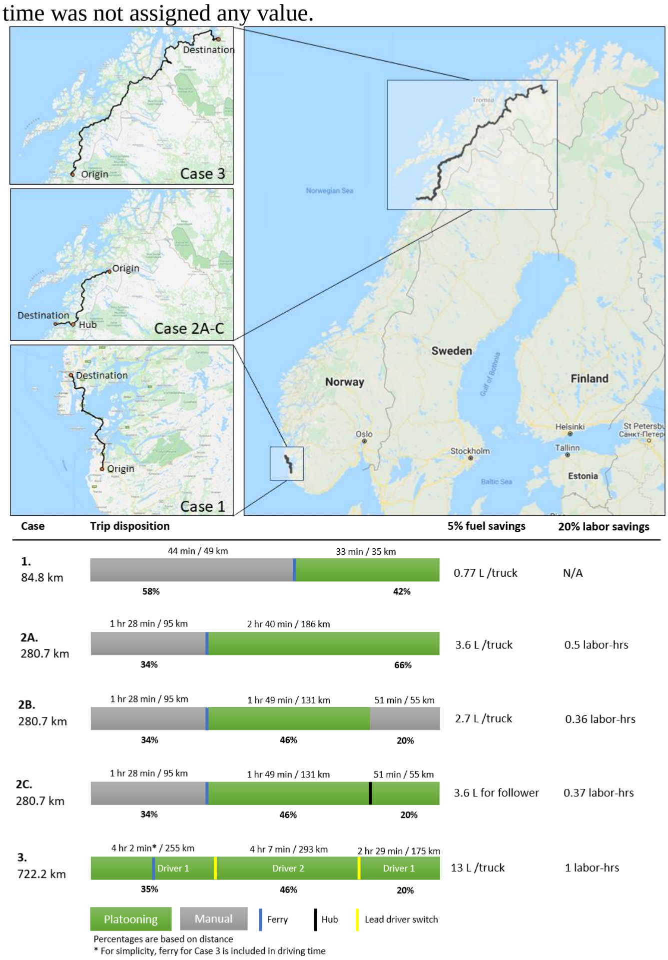

Figure 2: Simplified overview of cases

RESULTS AND DISCUSSION

This chapter contains a synthesis of participants' viewpoints on platooning in rural Norway, including discussions evoked from case examples. Study findings are grouped under six higher-order themes: Understanding of truck platooning (1), Impacts on truck drivers and hours-of-service regulations (2), Societal impacts and public acceptance (3), Logistics, organization, and cooperation (4), Economic considerations for shippers and carriers (5) and lastly, Infrastructure readiness, investments, and maintenance (6).

Table *1* provides a summarized overview of the opportunities and barriers discussed for themes 2 through 6, followed by suggestions for deployment and future research needs. The first theme, exploring participants' understanding of the truck platooning concept, is documented in a separate paragraph, and not included in the table. The subchapters following the table describe results and discussions for themes 2 through 5 in further detail.

Table 1: Results overview

	OPPORTUNITIES	BARRIERS	DEPLOYMENT SUGGESTIONS	RESEARCH NEEDS
TRUCK DRIVERS	• Safe and economic driving • Better utilization of driver competence • Improved workload management, trust, and comfort • Enable drivers to perform non-driving tasks or rest while moving • Enable drivers to return home at night	• Added demands for driver monitoring of platoon system and boundary conditions (ODD) • Diverging driving styles preferences between lead and following drivers • Reduced independence and freedom for drivers	• Designated leaders on challenging routes akin to skilled marine pilots in ports • Rotate truck positions to optimize driver workload • Small-scale introduction within companies • Form agreement about driving behaviors prior to platooning • Gradually extend driving periods	• Perceived usefulness and ease of use • Impacts on driver role, workload, and job satisfaction • Trust in technology and lead driver • Basis for changing hours-of-service regulations
SOCIETY	• Optimize handling of present freight volumes • Make existing tailgating practices safer • Improve intermodality • Ensure reliability of supply • Improve safety and accessibility for other road users • Reduce need to overtake • Prevent speeding and risky driving	• Changes in perceived control for shippers and receivers • Threat against political objectives for goods transfer from road to rail and sea • Public concerns about platooning safety • Public concerns about encountering platoons • Other road users' willingness to cooperate with platoons	• Clarify societal objectives • Incremental introduction to foster public acceptance • Communicate benefits to local inhabitants • Inform other road users • Introduce platooning for electric trucks	• Public acceptance • Traffic implications • Other road users' cooperation with platoons • Objective risks and safety effects

	OPPORTUNITIES	BARRIERS	DEPLOYMENT SUGGESTIONS	RESEARCH NEEDS
ORGANIZATION	• Complement directional freight balance • Simplify logistics planning • Regulate and sanction unfair behavior • Improved efficiency at terminals	• Inadequate truck volumes • Carriers not willing to cooperate • New scheduling demands • Waiting times • Cargo security • Data-security • Terminals becoming bottlenecks	• Target cargo that has high volumes and/or regularity • Target origin-destination pairs with high road freight volumes • Target ferry-dependent areas • Utilize infrastructure at low-intensity time windows • Matchmaking tool for carriers • Organize platooning in-house or cooperate with others • Platooning on fixed schedules	• Viable routes • Responsibility for organizing platoons • Matchmaking tool requirements • Data-sharing issues • Interface with other transport modes and terminal handling
ECONOMICS	• Reduced transport times and labor costs • Fuel savings • Improved utilization of driving, working and rest periods	• Start-up costs • Potentially limited fuel savings compared to other measures • Inadequate labor savings if drivers are needed in all trucks • Waiting time costs • Contrary views of being platoon leader (costs vs. job motivation)	• Conduct trials and pilots • Subsidies or marketplace exclusion • Software system for fair distribution of costs and savings	• Transport time reductions • Cost-benefit of waiting time • Fuel and labor savings • Models for co-financed R&D programs
INFRASTRUCTURE	• Address current road shortcomings for all users • Improved road capacity • Enable highly automated driving • Reduce interaction with other road users	• Lack of uniform, high-quality road infrastructure • Lack of truck stops • Winter conditions • Narrow, steep, and winding roads and tunnels	• Start in greater Oslo-area • Start on roads approved for EMS road trains • Alternating 2+1-lanes will enable overtaking and support emergency vehicles • Remove bottlenecks • Build more roadside pockets and climbing lanes	• Evaluation of road parameters • Impacts on road capacity • Winter operation demands • Basis for changing regulations (speed limits, overtaking)

Understanding of truck platooning

Participants expressed varying knowledge about platooning. Three participants, one researcher and two shipper representatives, had no prior knowledge of platooning. The most common expressions used to explain platooning were connected trucks driving as a chain, or road train. There were uncertainties regarding the criteria for using the term *platooning*, related both to the minimum automation level, and to the number of connected trucks needed in order for them to be considered a platoon. One interviewee compared platooning to vehicle-to-vehicle (V2V) communication between passenger cars, proposing that the main difference is that platoons have a "*lead sheep.*" Some emphasized the role of the lead truck in controlling following trucks, citing prospects of driverless followers. One interviewee saw platooning as "*a way of reducing the complexity of automation on road by having a driver in front, while increasing the freight volume and making it more dynamic.*" Several participants, representing interest organizations, an OEM, carriers, shippers and the NPRA, spoke of platooning as an exciting prospect. Some researchers and carriers, however, were skeptical. "*My first thought was Australian, enormous heavy goods vehicles, a mountain of vehicles.*"

Impacts on truck drivers and hours-of-service regulations

Several interviewees believed that all platooning trucks would require human driver presence for many years to come. They stated that this will depend on the extent to which technology can cope with everything that platoons can encounter on rural roads, e.g., curvature, tunnels, overtaking situations, vulnerable road users, wild animals, and adverse weather. While some uncertainties may be handled through regulations and infrastructure improvements, others will still require human driver intervention. Some suggested designated platoon leader roles. Experienced drivers familiar with local road conditions may enhance economical, defensive, and predictable driving, beneficial both for the platoon and other road users alike. To further utilize driver resources, non-driving tasks, such as loading and offloading, could be allocated to other roles. This would disburden the lead driver, who now carries responsibility for, and makes operational decisions for, the entire platoon while driving. Platooning could also introduce new work processes for drivers, such as operational maneuvers required to join and leave platoons. Strategical processes could also be introduced, such as trip planning and coordination with logistics dispatchers.

Increased automation could offer the opportunity for drivers to perform non-driving tasks while moving. However, drivers may experience increased mental demands if expected to monitor the driving operation for prolonged time periods. As far as drivers are required, platooning technology will add complexity to the driver-vehicle-environment system, in which the driver may be requested to intervene. Thus, interviewees were skeptical to scaling down training and licensing requirements for drivers in following trucks. If extended driving periods are permitted, or drivers can rest in-motion, some interviewees expressed concerns regarding performance of drivers in subsequent manual driving. On the flipside, fatigue may be alleviated by regularly rotating lead and follower positions. In this way, manual driving and monitoring tasks are evenly distributed between participants, as exemplified in case 3. Thus, the authors suggest that platooning could improve driver performance and traffic safety compared to individual driving, subject to the same automation level.

Some interviewees expected that challenging road conditions and diverging driving styles can evoke emotional and bodily responses, such as motion sickness, tension, and anxiety for following drivers. One participant suggested that platooning should first be introduced within smaller carrier subdivisions, where drivers know and trust each other, their cargo and equipment, before organizing platoons across business units or carriers. Forming agreements prior to platooning could also clarify expectations and increase predictability, trust, and comfort among drivers. Interviewees stated that some drivers may find driver team participation rewarding and possibly enjoy performing non-driving tasks while moving. Others, on the other hand, may feel constrained or pressured to platoon, appreciating the independence and freedom of solitary driving. Extended driving time may enable drivers to return home at night after long-haul trips but could also add to driver exploitation. Thus, platooning may have mixed impacts on job satisfaction, driver recruitment and staff turnover, as long as drivers are required.

Societal impacts and public acceptance

Stakeholders discussed barriers for public acceptance when introducing platooning on public roads. The OEM representative drew an interesting parallel between implementation of platooning in society, versus the process of continuous improvement in the industrial sectors. The industrial workforce is well acquainted with continuous negotiations between technologies and regulations to improve work processes. On the other hand, a step-change shift in mindset is required by society to accept platooning. Some interviewees stated that an incremental introduction, supported by good communication of positive effects for local inhabitants, would enhance public acceptance. Examples of such effects are traffic safety benefits and economic gains. Two interviewees pointed to conventional trucks driving closely today. Although tailgating practices are undesirable and prohibited, it appears to be socially acceptable in certain areas, and in certain driver populations. Therefore, platooning could be viewed as a means towards making current practices safer. According to one interviewee, public resistance towards platooning may be caused by erroneous predictions of increasing numbers of trucks, even if actual truck volumes were unchanged. Similarly, others posited that the total number of trucks one would encounter on Norwegian roads would not increase simply if platooning were to become feasible. Stated otherwise, platooning would *group* trucks together, causing motorists to encounter them *less* frequently. And even if road freight volumes were to increase, encountering a platoon of 5 trucks might not be too different from encountering one with three. As such, it is conceivable that platooning can absorb induced volume demands from a potential modal shift. The authors suggest that acceptance might be enhanced by ensuring that the public has a clear understanding of platooning and its traffic implications.

At large, the Norwegian public trusts its policymakers, who do not permit new technologies until proven safe. Still, several interviewees demanded more testing and knowledge of platooning safety effects. Two interviewees mentioned that motorists may feel overwhelmed when approaching truck platoons on narrow roads with limited sight distance, perceiving this as unsafe, although the objective risk may not differ from meeting conventional trucks, one by one. Nevertheless, this perception could weaken public acceptance of platooning. To gain public acceptance and promote safety, participants stated that motorists must somehow be informed about the presence of platoons, potentially by means of variable signage. While most were concerned with overtaking, others questioned the need for this, seeing platooning as a convenient opportunity to prohibit speeding and risky driving. These participants also alluded to a future where overtaking of platoons may have become banned and passenger vehicles are instead able to join them. Some interviewees stated that, over time, public perception may lead to a future where overtaking is no longer considered an issue: *"I think it's great if sometime in the future a family who are going on a holiday trip from Oslo to Trondheim can just connect to a platoon."*

Introduction of platooning were often discussed by interviewees in relation to other freight modes. Despite political objectives for goods transfer from road freight towards rail and sea, several interviewees pointed to increasing road freight volumes and sparse changes in modal proportions in recent years. Directly related to political ambitions, interviewees mentioned desires to improve traffic safety through reducing heavy vehicle numbers. Other stated ambitions were to stimulate business development in rail and sea transport, minimize ecological footprints and reduce emissions. Some acknowledged the unmatched efficiency and flexibility of road freight. As stated by several interviewees, electrification of trucks would weaken the sustainability argument underpinning the goods transfer objective. Two interviewees also mentioned the advantage of platooning in ensuring reliability of supply during emergency and peacekeeping situations, where the capacity and flexibility of other routes and freight modes may be constrained. Nonetheless, as the OEM representative suggested, a shift in mindset might be required. Platooning, although more flexible than rail and sea freight, will cause changes in locus of control of businesses and society: *"You can decide exactly when you want to send it and when it will arrive. (...). And we like to be in control. [Platooning] changes all of this. And that's hard.*"

The authors state that the motivation behind platooning may not be to expand road freight at the expense of other modes, but rather to optimize handling of present volumes and improve intermodality, as exemplified in case 3. As one interviewee highlighted, higher-level societal objectives could be clarified and current practices improved, while retaining ambitions for other modes. Some suggested that platooning on rural roads could maximize roadway uptime and availability, through infrastructure improvements facilitating platooning. It was postulated that such improvements would have positive effects on accessibility and safety for local road users and industries. This could possibly attract new citizens and contribute to economic growth in rural areas. Others, on the other hand, believed that efficiency gains would strengthen ongoing tendencies towards centralization.

Logistics, organization, and cooperation

To facilitate coordination of trucks meeting to form a platoon, one would ideally have sufficient volumes throughout the entire day, or at least during peaks from industry clusters. One participant suggested targeting high-regularity non-perishable goods, which are presumably less sensitive to wait times than goods with shorter lifespans. Others saw farmed fish as a good candidate, based on large current volumes, and forecasts of increasing production volumes in the future. Some suggested that carriers could organize platooning in-house if they have sufficient volumes, or they could cooperate with others. Many non-carrier representatives were skeptical to the realism of between-carrier cooperation, rooted in the competitive nature of the industry. According to these interviewees, small carriers may fear increased competition from larger ones. Larger carriers, on the other hand, might not want to cooperate since this could disproportionally benefit small carriers. Many emphasized that carriers do not fancy sharing, preferring to own the whole value chain. However, carrier representatives were mostly positive towards such collaboration. While this could indeed reflect their true intentions, it could also project a wish to present their company as overly forthcoming towards collaborative efforts. With respect to start-up costs, several interviewees suggest that platooning pilots could be organized by larger carriers, possibly supported by public funding. Later, subsidies or marketplace exclusion of non-platooning actors could force or motivate the industry to collaborate.

A representative from an interest organization stated that a matchmaking tool is needed for organizing platoons across carriers: "*one needs the Tinder of goods,"* referring to the popular dating app. The interviewee also stated that platooning will be most feasible if it can somehow complement directional freight balance between origin-destination pairs, which is a challenge in Norway. Although the need for matchmaking may first appear as a logistical barrier, one interviewee noted that such a system could potentially offload dispatchers and logistics planners. A matchmaking tool resonated with many interviewees, as it would embrace small carriers and could be organized to prevent unsportsmanlike behavior. An interviewee knowledgeable in roadside heavy vehicle inspections, suggested an example: A lead driver could deliberately slow down a platoon of trucks from competing firms, allowing another representative from his company to arrive first at a terminal.

Interviewees from most stakeholder groups noted that data-sharing should be independent of truck brands and fleet management systems. It was also suggested that carriers may exchange scheduled departures and destinations, along with truck weights and equipment status. This could be done in real-time, through a system akin to shipping and airline AIS (Automatic Identification System). To what extent location-sharing and platooning should be allowed for dangerous goods, such as natural gas shipments, remains an open question. Matchmaking could also include a scoring system where drivers rate the leader, or driving behaviors are objectively recorded. Data security was stressed, some suggesting the use of authentication protocols to validate participant integrity. Ideas were discussed as to who should own the matchmaking system, e.g., the Norwegian Truck Owners Association, the NPRA, carriers or even shippers involved in platooning agreements. Others drew parallels to the Norwegian state-owned rail freight company, suggesting organizing platooning in the same way, or even as a subsidiary of this public entity. Some felt that platooning would be better organized by the transport industry itself, emphasizing that it should have multiple owners to avoid monopolistic tendencies. The system owner could regulate and sanction unfair behavior, as well as accept trucks and drivers into the network. The authors suggest that a public system owner could either create and operate the matchmaking software in-house, or specify its workings, procure it, and regulate its use through a private entity. Regarding regulatory approval on the NPRA level, some suggested that platoons could be organized as a vehicle class or subcategory under the EMS framework.

Platooning could be organized in advance, through timetables and fixed agreements. Coordination hubs, as suggested in case 2, could be established and agreed upon, from which platoons would depart on fixed schedules. Platooning could also happen in a spontaneous, ad-hoc fashion while driving, or a combination of both. Some regions may not have enough goods flows, being constrained by infeasibly long wait times at hubs. "*Once you have to wait for 5 minutes, I think it becomes less relevant. But if you can get a match while driving, I think it will work much better*." Platooning in such areas may require more upfront coordination. Wait time variability is also an important aspect, especially for remote hubs. Given high variability, drivers and carriers might be less inclined to wait.

Before introducing the cases, a county representative suggested looking at ferry-dependent areas, where travel is already contingent on departure frequency and often involves waiting. Some objected based on infrastructure quality, as roads with ferries typically have lower standard due to adverse topography. Others objected due to small volumes on such routes. Some also stated that ferry prices are expensive for trucks, carriers preferring alternate routes if available. Nonetheless, as the case examples indicate, several locations in Norway have ferries as the only option. Many of these also have sufficient truck volumes for platooning.

An interviewee knowledgeable in rail terminal operations, stated that terminals may need to be scaled up to handle platoons, as these might currently represent bottlenecks. He suggested it would be easiest to operate trucks separately at terminals, linking them on the outside. Moreover, he suggested using formal agreements to incentivize carriers to stick to their drayage agreements. Monetary penalties could be used to avoid excessive build-up of terminal inventory, which is a current challenge. Fearing market share transfer, some proposed allowing platooning only as part of intermodal chains, combining road, rail, and sea. Some researchers suggested reorganizing the structure of driving jobs: Most truckers could operate as local feeders between production facilities or terminals in one end, and hubs located adjacent to arterials in the other. One researcher referred to this model as "*a public transport trip for goods*." Platooning could be organized at specific times-of-day, during seasons where passenger transport is limited, or during periods void of problematic winter conditions. Platooning could even be restricted to one arterial direction during certain weekdays. In Norway, a handful of origin and destination pairs exists which are connected by parallel, high-volume routes. The two roads between Oslo and Trondheim provide a good example. Conceptually, platooning could be allowed in one direction along one of the routes, and in the other direction along the other route. Moreover, the directions could alternate daily to limit the burden on commuters and local inhabitants. It could be communicated to the public whether motorists should expect meeting platoons or catching up with them. A researcher pointed out that data on actual origin-destination pairs for truck trips would be beneficial for understanding where platooning would work from a volume perspective.

Economic considerations for shippers and carriers

Stakeholders agreed that platooning will only be viable if it improves carrier competitiveness. Carrier representatives, in particular, stated that fuel savings are unlikely to be sufficiently appealing to adopt platooning, and that these might even be outweighed by simple measures such as speed restriction or maintenance optimization. Labor cost and lead time reductions were regarded as more important: "*I really think [platooning] will not be profitable until you can remove driver number 2 and 3.*" As long as drivers are required in all trucks, carriers could utilize driving, working and rest periods across several drivers on the same route. As exemplified in case 3, saving may arise from switching order in the platoon if drivers in following trucks can rest while in motion. This could significantly reduce transit time for longer trips, allowing carriers to take on subsequent assignments earlier, while increasing asset allocation and allowing operation of a smaller vehicle fleet to obtain the same delivery numbers. Some participants stated that owner-operators are often paid fixed prices based on volumes and distances, regardless of the time required to complete assignments. Reduced transit times, however, might lead to "*(…) more urgent assignments where the transit time is important.*" One interviewee suggested that this might increase the number of high-margin assignments, perhaps at the expense of decreasing carrier ability to plan operations in advance, making planning a more expensive task. The authors suggest that this could be alleviated by a responsive matchmaking system.

The idea of paying followers lower hourly wage, introduced in case 2A, was opposed based on labor practices and the possible rotation of driving tasks towards other tasks such as coordinating upcoming assignments. Excluding owner-operators, it is unclear how drivers will be incentivized towards forming platoons. There might even be contradictory views between drivers and executives: "*The same company may not want to drive first all the time. At least not the business owner, because doing so is more costly. While the driver may want to drive first*." A software solution would likely be needed, where platoon savings are distributed fairly between participants. One solution could be that some of the savings from platooning could accrue to the driver. One interviewee stated that platooning would be a clear example of platform economy, transforming it into more of a cooperative activity than it currently is. She continued by stating that platooning is likely to remain unprofitable as long as fuel savings is the parameter optimized for, suggesting optimizing for safety or traffic flow instead. Others stressed that the software must facilitate payment between carriers of multiple nationalities, considering the international nature of the industry. In addition to studying specific case routes for platooning, one interviewee suggested establishing a more rigorous framework for investigating economic matters. He proposed that such a framework could include, among other aspects, platooning distance, number of vehicles, number of drivers (dependent on the automation level in each truck), transit time, hours-of-service regulations, and inter-vehicle headway.

Waiting at coordination hubs entail economic costs. Carrier representatives mentioned driver salary, carrier profit margin, and depreciation of the vehicle and cargo. They also pointed out that drivers are constrained by hours-of-service regulations, running the risk of depleting their daily allowed working hours due to waiting, since shipments are currently planned to fully utilize working time. Drivers might also be late with respect to scheduled delivery time, and thus prevented from waiting. One interviewee pointed out that waiting might not necessarily constitute a cost if the wait at the hub were to coincide with breaks required by hours-of-service regulations. As such, metrics pertaining to breaks and remaining driving periods of each driver, could also be included in the matchmaking algorithm.

Infrastructure readiness, investments, and maintenance

Most of the Norwegian road network constitutes two-lane roads with large topographical variations. Interviewees expected that platooning will require high-quality, uniform infrastructure standard and consistent geometric alignment, including horizontal curve radii and sight distance. Many stated that platooning would be feasible only on newer multi-lane roads, as opposed to two-lane roads. Some suggested that platooning would gradually be allowed on the secondary road network when proven sufficiently safe and reliable. To mitigate infrastructure shortcomings along main corridors, interviewees focused both on general features and removal of bottlenecks on specific routes. Avoiding abrupt changes in road quality was mentioned as important for minimizing the need for manual intervention by drivers in following trucks. This would also prevent unwanted interaction with other motorists. Some participants suggested that the NPRA could explore whether road sections approved for EMS road trains could be applicable also for platooning. In this way, future expansions of the EMS network could account for both vehicle classes simultaneously.

Inspired by deployment scenarios in other countries, one interviewee suggested dedicating one highway lane for platooning. This seems infeasible, however, due to generally low truck volumes and few multi-lane roads. One interviewee suggested looking at platooning use-cases starting in the greater Oslo-area, as this region has large motorway proportions and an extensive terminal structure for goods consolidation. Most interviewees were skeptical towards motorists overtaking platoons on two-lane roads. At the same time, potential positive effects of platooning on road capacity were discussed. Truck platoons could reduce speed variability while occupying less longitudinal space compared to manual driving. Some interviewees questioned the Norwegian standard of building two-lane roads that, they stated, do not adequately address bottlenecks such as narrow and steep segments. Three-lane highways, or so-called alternating 2+1-roads, were seen as a minimum to enable frequent overtaking both for motorists and for emergency response vehicles. For existing two-lane roads, interviewees proposed establishing roadside pockets and increasing the number and length of climbing lanes at narrow passages and steep grades. This would overcome current issues related to passing lanes, many having inadequate length, being too short to allow a convoy of trailing passenger vehicles to overtake platoons.

Some stated that platooning would demand more comprehensive road maintenance and operation, citing this also as economic and organizational barriers. Conversely, others saw this as a traffic safety benefit that would accrue to local inhabitants and other road users. Some questioned platooning in winter from a public safety perspective. Two interviewees proposed that criteria for operation and maintenance contracts should reflect freight volumes to a larger extent than is the case today. One interviewee discussed the effects of platooning on the road substructure, pointing to knowledge gaps as to how platooning might require additional reinforcement. Some pointed out the usefulness of hubs and proposed expanding, or otherwise adding such functionality to existing truck stops. A recurring theme in carrier interviews, was lack of truck stops along Norwegian roads. Some mentioned that truck stops are inaccessible during winter due to lacking snow removal. Expanding the number of truck stops in strategic locations and improving winter operations, might both address current carrier needs, and facilitate meeting places where platoons can form and dissolve.

Figure 3 visualizes specific road-stretches most frequently mentioned by interviewees as viable for platooning. Note that *viability* in this case denotes a multifaceted aspect, including freight volumes, organizational ease, road standard, operational demands, and impacts on others. As such, platooning will only be possible on the displayed routes if all viability aspects meet certain minimum criteria. These criteria, however, need further specification. Figure 3 includes some of the routes from the case discussions, in addition to other routes that were freely explored by participants. Several individuals stated that platooning should be most easily achievable on stretches with national road standard. Routes in the Eastern part of Norway generally seem most suitable, as these have the highest motorway proportions and largest truck volumes, while being far less impacted by adverse topography compared to Northern and West-coast routes. The two parallel Oslo-Trondheim corridors were most frequently mentioned. Routes to and from smaller coastal seafood industry destinations, e.g., Hitra and Rørvik, and the greater Oslo area, were seen as viable from a volume perspective. The route between Oslo and Narvik, traversing Sweden, was also mentioned. Truck shipments between Southern and Northern Norway often traverse through Sweden, due to better road standard and higher speed limits. In general, such long-haul routes could benefit greatly if hours-of-service regulations would allow for continuous operation. This would require the creation of a formal hub structure to facilitate platoon coordination along the route. Naturally, the same is true for other domestic origin-destination pairs which currently require overnight rest.

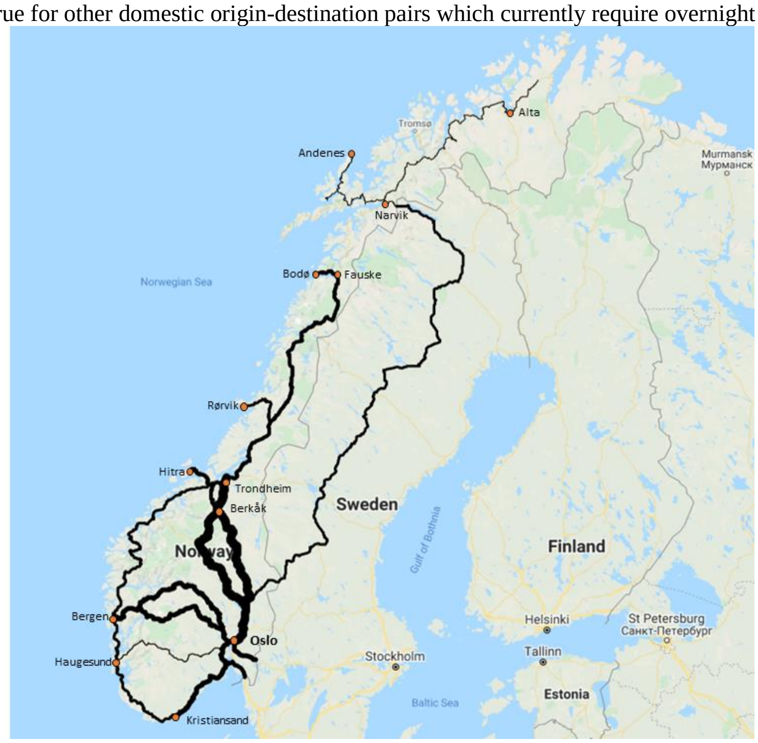

Figure 3: Routes with domestic origins and destinations most frequently mentioned by participants as viable for platooning. Line thickness indicates relative frequency of mentions.

Another issue in Norway is the prevalence of road tunnels. A few interviewees state that while many are in good condition, some are old and narrow, falling below requirements for e.g., maximum grades and lighting levels. In steep tunnels, platooning trucks should have similar ratios between weight and engine power. If headway distances are quite small, cooling of combustion engines might also be an issue for uphill tunnel grades. The authors underline that it is unclear to what extent platooning should be allowed in tunnels, with respect to brake and transmission components overheating, as the severity of platoon accidents might be larger than for individual trucks.

Although generally seen as vital, interviewees were uncertain as to what type of digital infrastructure platooning might require, and the extent of such infrastructure. A county representative stated that all new roads in his jurisdiction are built with cable conduits for expected power and fiber cables. Some brought up cellular coverage and broadband connection, pointing out that there are "*substantial cellular dead zones*" across large parts of Northern Norway. These, however, are likely to get resolved during upcoming 5G network implementation. It is also unclear to what extent roadside communication is required for connectivity between platooning trucks.

Some interviewees, particularly researchers, stated that cost-benefit analyses should be carried out to assess which routes deserve infrastructure improvements. Routes which might be generally well-suited, but have patches where investments are needed, should be prioritized above those where comprehensive work is required.

CONCLUSIONS

The present study investigated opportunities and barriers for platooning in a rural context with modest freight volumes, geographically dispersed industries, and challenging road conditions. Through their freight transport expertise, interviewed stakeholders identified several prerequisites for platooning in this context. While some carriers may have sufficient demands and regularity to enable platooning on their own, a matchmaking system could expand the potential to carriers and areas with lower volumes. While fuel savings seem insufficient for profitable platooning, reduced transit times and driver costs present economic opportunities. The extent of such savings will depend on readiness and harmonization of vehicle technology, infrastructure, and organization. Additionally, lower speed variability could reduce accident numbers. Platooning may require certain road alignment, sight distances, climbing lanes, traffic separation and digital communication features. If so, such characteristics should be considered today in long-term infrastructure planning and investments.

As with any novel technology, acceptance is a prerequisite for adoption. This implies that truck drivers, other road users and the public find platooning favorable, safe, and easy to use or cooperate with. Currently, many see overtaking as a barrier for platooning, which could justify increased operational spending and investments towards multi-lane roads. However, technological advances and organizational means could diminish motives for overtaking. Technology may also, to some extent, counteract infrastructure shortcomings and coordinate road users. For instance, speed limits for opposing traffic may automatically change to facilitate safe meeting of platoons, avoiding bottlenecks on the road. Similarly, Cooperative Intelligent Transport Systems (C-ITS) applications may assist trailing motorists in overtaking when there is limited sight distance. Moreover, platooning is developing alongside rapid advances in passenger vehicle automation. In the future, it is conceivable that motorists are able to join truck platoons.

We have identified several barriers to overcome. Platooning will require re-evaluation of road parameters and infrastructure management. How to make a matchmaking system beneficial for platooning, also in low-volume areas, needs further investigation. The demands for platoon drivers to monitor and intervene in challenging road and weather conditions should be clarified to justify regulatory changes. Platooning may have mixed impacts on truck drivers, both relating to the driving task and job satisfaction, geographical work patterns, cargo management, and terminal handling. A framework for studying platooning viability should consider multifaceted metrics, such as freight volumes, organizational ease, road standard, operational demands and impacts on others. Analyses of real-world carrier shipments could complement modelling of future deployment scenarios.

This paper showcases the need for a holistic approach that captures all aspects of platooning on challenging freight routes. Further efforts should pay attention to public and private stakeholder needs by involving them in study planning and evaluation of findings. Real-life testing is imperative for acceptance, and thereby also for successful adoption of new technologies. Previous platooning trials on public roads have been performed mostly on motorways. These roads have homogenous speeds and forgiving roadway alignment. Testing on two-lane roads would showcase the state of platooning technology, while indicating the current level of infrastructure readiness. Such field-studies would also provide insights into economic, organizational, and safety-related impacts of platooning in a rural context. The authors suggest iterative field-studies as part of long-term research efforts to better understand the conditions under which platooning is viable and beneficial for society.

Truck platooning is forecasted as one of the earliest applications of road vehicle automation to commercialize. For Norway to benefit from this advancement, with its conditions and rural contexts, timely and coordinated action is needed on multiple areas.

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The authors confirm contribution to the paper as follows: study conception: M. H. R. Eitrheim, M. M. Log, T. Tørset, T. Levin, K. Pitera; study design: M. H. R. Eitrheim, M. M. Log; data collection: M. H. R. Eitrheim, M. M. Log; analysis and interpretation of results: M. H. R. Eitrheim, M. M. Log, T. Tørset; draft manuscript preparation: M. H. R. Eitrheim, M. M. Log. All authors reviewed the results and approved the final version of the manuscript.

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Paper 2

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Article

Using Low-Cost Radar Sensors and Action Cameras to Measure Inter-Vehicle Distances in Real-World Truck Platooning

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Abstract: Many modern vehicles collect inter-vehicle distance data from radar sensors as input to driver assistance systems. However, vehicle manufacturers often use proprietary algorithms to conceal the collected data, making them inaccessible to external individuals, such as researchers. Aftermarket sensors may circumvent this issue. This study investigated the use of low-cost radar sensors to determine inter-vehicle distances during real-world semi-automated truck platooning on two-way, two-lane rural roads. Radar data from the two follower trucks in a three-truck platoon were collected, synchronized and filtered. The sensors measured distance, relative velocity and signal-to-noise ratio. Dashboard camera footage was collected, coded and synchronized to the radar data, providing context about the driving situation, such as oncoming trucks, roundabouts and tunnels. The sensors had different configuration parameters, suggested by the supplier, to avoid signal interference. With parameters as chosen, sensor ranges, inferred from maximum distance measurements, were approximately 74 and 71 m. These values were almost on par with theoretical calculations. The sensors captured the preceding truck for 83–85% of the time where they had the preceding truck within range, and 95–96% of the time in tunnels. While roundabouts are problematic, the sensors are feasible for collecting inter-vehicle distance data during truck platooning.

Keywords: inter-vehicle distance measurements; radar sensor; action camera; field study; automated truck platooning; rural road; manual video coding; field-of-view; tunnels; roundabouts

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1. Introduction

Truck platooning refers to the innovative concept of wirelessly linking trucks into convoys using adaptive cruise control (ACC). Platoons consist of one lead truck and one or more following trucks. Wireless communication may enable shorter inter-vehicle distances than those currently considered safe for manually driven trucks, which are constrained by the reaction times of human drivers [1,2]. Shorter inter-vehicle distances lead to a reduction in aerodynamic drag, which may enable fuel savings and reduced emissions. Moreover, tight, automated vehicle control may unlock improvements in safety and efficiency of the road traffic system [2]. Platooning may also benefit society at large, in terms of cheaper, safer and more streamlined road freight operations. However, platooning is yet to be commercially deployed and there are many unanswered questions.

Field studies are often used to explore the technology and are organized either by transport companies [3] or truck manufacturers directly [4], or through larger, publicly funded undertakings, such as the KONVOI [1] and ENSEMBLE projects [5]. The studies have typically been conducted on highways. Few studies, if any, have investigated platooning on challenging two-way, two-lane roads with oncoming traffic and narrow tunnels. In Norway, for example, large parts of the road network are subject to such issues, on which more research is needed to establish the feasibility of truck platooning. Public roads authorities govern the design and operations of the road network and may thus be important facilitators of truck platooning. As Norway is a small automotive market with conditions for automated vehicles, the Norwegian Public Roads Administration (NPRA) have taken a proactive role in trialing advanced transportation technologies, exemplified by the Borealis testbed [6] and the ongoing MODI project [7], which aims to demonstrate automated trucking between the Netherlands and Norway within 2026.

In general, the shorter inter-vehicle distances are between platooning trucks, the greater are the resulting benefits in terms of fuel savings and potential road capacity improvements. Thus, the greater the stability of inter-vehicle distances over time, the more beneficial platooning will be [8]. However, during real-world driving, combinations of external traffic, road alignment and truck weight differences will influence the inter-vehicle distances, and thus also the extent of benefits unlocked [9,10]. Moreover, the extent to which truck platoons impact surrounding traffic depends partly on their total length, which is influenced by inter-vehicle distances. By implication, inter-vehicle distance data will be important for public roads authorities when regulating truck platooning, such as when deciding on which road sections platoons should be allowed, and the maximum number of trucks which can platoon together. However, such data may not be easily accessible, and even if they were, it is unclear how they should be contextualized and analyzed.

In the field studies organized through the large, aforementioned platooning projects, truck manufacturers and transport companies have typically facilitated and allowed for the collection of inter-vehicle distance measurements using integrated vehicle sensors. While integrated distance sensors could also be cameras and lidars [11], radar sensors are most often used, as they are affordable, computationally simple and robust under adverse light and weather conditions [11–15]. This is despite issues with clutter [16] and ghosting [17], referring to unwanted signals that distort and interfere with the desired detection, and the detection of non-existent targets which are difficult to distinguish from real ones.

If allowed, using data from integrated vehicle sensors is very convenient, as they are already collected as real-time inputs to platooning control systems, removing the need for using aftermarket distance sensors. However, manufacturers often use proprietary algorithms for data processing, defining message codes [18] to encrypt collected data. This makes external individuals unable to access them, unless authorized to do so. Smaller truck platooning field studies may not have the benefit of truck manufacturers participating as partners. Some may also seek to verify data from manufacturers, for which independent methods for collecting such data would be useful.

High-precision global navigation satellite system (GNSS) receivers located in successive vehicles could theoretically be used for this purpose [19,20]. Some areas, however, have road tunnels and topographical features where GNSS-based data collection methods would be subject to signal blockages [12,20]. External aftermarket radar sensors may circumvent the problem, provided they are adequately practical and accurate. Truck platooning research is often publicly funded, so solutions should preferably be low-cost. Since the output of aftermarket radar sensors would not be used for operative vehicle control, they do not need to be as capable, nor provide the same level of reliability as automotive-grade distance sensors, both of which drive cost and complexity. They may also be more flexible, in terms of allowing for custom placement and user adaptations.

Many researchers have focused on perception, functional safety and operative control for truck platoons [21]. These studies often include cameras and radars. However, for studying the effects of truck platooning from the standpoint of roads authorities, these methods are more computationally complex than they need to be, and simple methods for estimating inter-vehicle distances from truck platooning would be useful.

The current study investigated the feasibility of using Anteral universal radar (uRAD) sensors for Raspberry Pi [22] to measure inter-vehicle distances in a truck platoon on rural roads. This application represents a novel use case for this type of sensor. We propose a multi-faceted approach for collecting inter-vehicle distance data from truck platooning field trials. It aims to provide technical details and best-practices on data collection, synchronization, filtering and analysis. Dashboard cameras in each truck filmed the driving scene. This footage was used to log the timestamps of specific, recurring events, allowing for exploring sensor operation in different driving conditions.

The paper addresses the research question: How can low-cost radar sensors and action cameras be used to investigate inter-vehicle distances in real-world truck platooning?

2. Materials and Methods

This section provides details on the data collection set-up, the equipment used, and the procedures for synchronization, video coding and radar data processing.

2.1. Data Collection Set-Up

A truck platooning field trial was undertaken on public rural roads in northern Norway in the fall of 2020. This is the first study of its kind, and was also reported in [23]. Three drivers operated three semi-trailer trucks along a 380 km two-way, two-lane road stretch traversing a mountainous, coastal area. The trucks were numbered 1, 2 and 3, based on the main truck order configuration. One section was traversed repeatedly with different orders. A prototype ACC system was installed, enabling the trucks to operate as a platoon when detecting a preceding truck. Data from integrated cameras and radars were unavailable. Aftermarket equipment was used to collect data over 7 h of driving.

While longitudinal control was automated, the drivers operated the wheel manually, placing the field study at the Society of Automotive Engineers (SAE) Level 1 [24]. All trucks had 500 horsepower. Trucks 1 and 2 had equal weights, while truck 3 was lighter. (41 and 27.5 metric tons), reflecting the scenario of trucks encountering each other to platoon during real-world operations, unharmonized with respect to weight. Consequently, inter-vehicle distances fluctuated, as the platoon often struggled to remain collected on the winding road. Twenty-three tunnels and eleven roundabouts were traversed. The most prevalent speed limits were 80 and 60 km/h, during which inter-vehicle distances at 3-s time gaps were 50–70 m, i.e., comparable to manual driving. Figure 1 illustrates the set-up.

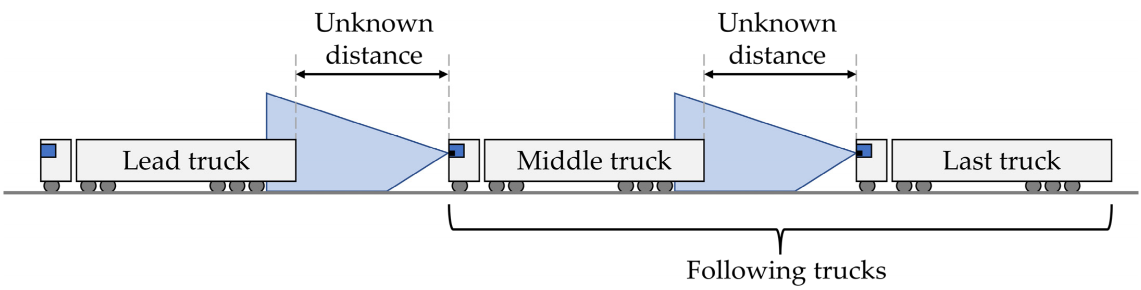

Figure 1. Truck platooning set-up. Radar sensors were mounted on windshields of following trucks.

Herein, *preceding truck* is a term used for the truck located in front of the truck in question. Depending on the context, it may refer to either the lead truck or the middle truck. In truck order 1-2-3, truck 1 precedes truck 2, and truck 2 precedes truck 3. The terms *leader* or *leading truck* are only used for the truck located at the front of the platoon, while *followers* refer to both the middle and last truck together.

The two rearmost trucks were identically instrumented. The Raspberry Pi, with the uRAD sensor attached, was fixed to the inside of the windshield using a suction mount with a flexible arm. The mount did not interfere with the field-of-view of the sensors. A portable monitor was used to administer radar logging. Sensors were placed at slightly different heights in each truck due to interior constraints, cf. Appendix A.1.

Two GoPro video cameras were also mounted: A windshield-mounted dashboard camera filmed the driving scene, and another camera filmed the interior. Footage from the latter was only used for synchronizing radar data to the dashboard footage. The study was approved by the Norwegian Centre for Research Data (457013). Participants agreed to being recorded, and all videos and audio were handled and stored confidentially.

The equipment in each truck was started and stopped in succession when trucks were parked, but was left on during short breaks. None of the Raspberry Pi microprocessors had internet connection, so they did not adhere to local time. An equipment start-up procedure was devised which allowed for post-hoc synchronization of videos and radar data. For each truck, all cameras were started before starting radar logging. When starting each camera, the Emerald Sequoia Time smartphone application was presented. Using Network Time Protocol (NTP) servers, which synchronizes computer clocks over the internet [25], this application provides more accurate times than those typically provided by internal clocks [26]. The application shows local time, and, when cellular reception is available, it calculates deviations from NTP time. The mean offset was 0.08 s, i.e., negligible.

GNSS data were collected from VBOX Sport loggers and a fleet management system (FMS), in an effort to compute inter-vehicle distances to validate the radar data. A script was written to interpolate timestamps and calculate distances between GNSS locations from each truck. The loggers were supposed to activate automatically [27], but this functionality occasionally failed. GNSS files were also extracted from the FMS, and all files were visualized in QGIS. Both systems experienced outages in tunnels. While the FMS had good positioning accuracy outside tunnels, its update rate was too low, and loggings were not always synchronized across the trucks. VBOX data which did get collected had frequent outages, and timestamps were often erroneous, placing trucks in incorrect order. This highlights the utility of radar in estimating inter-vehicle distances in such areas.

2.2. Radar Sensors

Frequency modulated continuous waves (FMCWs) are radar waveforms often used to measure distances in automotive applications [13,28]. Anteral uRAD radar sensors for Raspberry Pi were tested here, shown in Figure 2. These are 24 GHz FMCW radar sensors which connect conveniently as extension boards to Raspberry Pi microprocessors [29]. Such microprocessors run a user-friendly operating system and can interface with purpose-built components. The automotive industry is increasingly using 77 GHz radar sensors, allowing for increased range resolution and accuracy [30]. These sensors can better separate closely spaced objects, and can be packaged in a smaller form factor. However, 24 GHz sensors are less expensive, and automotive-grade 77 GHz sensors which could be operated from Raspberry Pi microprocessors were not available when procuring the equipment. Thus, testing the proposed methodology using cheaper 24 GHz sensors was considered reasonable. While many 77 GHz FMCW radar sensors are more range-capable and have wider fields-of view, some 77 GHz radars, e.g., in [31], have shorter ranges than the uRAD sensors.

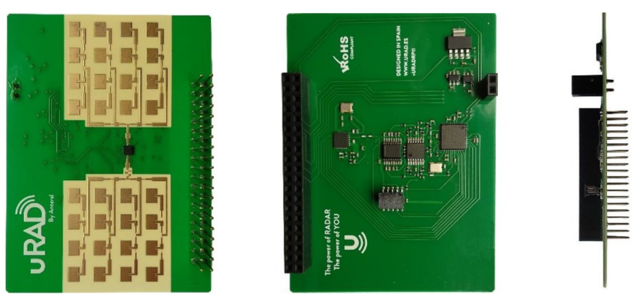

Figure 2. Radar sensor outline [22].

The uRAD sensors have a theoretical distance range approaching 100 m, 30° fields-of-view both horizontally and vertically, and are able to detect up to five objects simultaneously. For each object, distance, radial velocity and reflected power (SNR, i.e., signal-to-noise ratio) are registered. In the context of truck platooning, both the sensor and the desired objects are in motion; so *relative* velocities are detected. The velocity range (±0.2 to 75 m per second) is within the range of values encountered in road traffic.

The use case and intended sensor placement were described to the supplier, which expected the application to be feasible, but did note that similar tests had never been carried out before. The sensor has been used for other purposes, the most relevant of which is as a stationary speed sensor [29,32,33]. However, transferability from the cited studies is limited, due to different use cases and configurations.

Eight parameters were used to configure the sensors. These are detailed in Appendix A.1, alongside pre-trial testing of the mounting set-up and parameters. The most important considerations are detailed here.

Firstly, the radar mode details the waveforms transmitted by the sensor. Triangular waves were chosen, which maximized the sensor range and the update rate for outputs (9–13 Hz) from the radar script. This mode also allowed for subsequent data filtering based on relative velocity. Maximizing range was important for capturing data even when trucks were located far apart, as the trucks were expected to drive with human-level gap sizes (2–3 s) at distances approaching the upper distance range. Adverse road geometry would presumably also lead to safer driving at larger gap sizes. Maximizing the update rate was seen as beneficial for obtaining as many measurements as possible. The update rate of the uRAD radar sensor is comparable to the 77 GHz sensors showcased in [14].

Secondly, number of targets detected (N_{tar}) and the detection distance (R_{max}) were maximized, to capture the most data, and to enable filtering of unwanted detections later.

Thirdly, moving Target Indicator (*MTI*) was activated, for including data only from objects with motion relative to the sensor. The supplier stated that it would only eliminate objects which were absolutely static, such as detections of the windshield. The preceding truck would still be registered, even when moving at the same velocity as the sensor.

Fourthly, for each truck, different values for ramp start frequency (f_0) and the duration of each wave ramp (N_s) were used for each sensor to avoid interference. Since each sensor had different N_s and f_0 values, their theoretical maximum distance ranges also differed, at 75.0 and 73.1 m, for trucks 2 and 3, respectively, based on Equation A3 in Appendix A.1. These values are in line with 70–75 m estimates from the supplier. For comparison, automotive radar sensors typically have ranges of 30–150 m [30,34]. The sensors had a stated distance accuracy of ±0.3%, corresponding to a ±0.23 m deviation at 75 m, which is considered sufficient for the current use case. Table A3 in Appendix A.1 shows all parameters which were used.

2.3. Video Footage, Synchronization and Manual Video Coding

Dashboard footage was recorded for exploring the radar data as a function of the driving scene. Without the videos, this would not have been possible. First, footage had to be coded, i.e., timestamps had to be established for relevant events in the footage. This is different from the more computationally complex process of semantic segmentation used in computer vision, which involves categorizing relevant objects in the scene, often using bounding boxes [31].

Video footage was synchronized and aligned to local time using BORIS, i.e., Behavioral Observation Research Interactive Software [35]. BORIS is a free, open-source video coding program. Each BORIS observation contained videos from the same truck and driving stretch. By checking time differences as displayed by the phone application at the start of each recording, time offsets were established, achieving near-perfect synchronization. The date and time of each observation was defined as the local time shown by the phone application to the longest video file, as the recording was started. This ensured that all videos from the trucks were aligned to local time during the field trial.

Events in BORIS were defined using the ethnogram, and were either point or state events: Point events had no duration (i.e., having only one timestamp), while state events did (i.e., having both start and end timestamps). Video coding was carried out while playing videos at 2–4 times normal speed, depending on driving scene complexity. Events were coded by the first author, ensuring consistency. Videos codes were subsequently reviewed by the third author. Onwards, *italics* are used to refer to the video codes, as illustrated in Figure 3. Radar initiations (*Radar logging*) and oncoming traffic were defined as point events. Amongst oncoming vehicles, only *Trucks* seemed to affect inter-vehicle distances during platooning. Video footage showed that when encountering large trucks on narrow road segments, the lead truck often reduced its speed, causing speed reductions also for the followers and a contraction in inter-vehicle distances. Truck order codes indicate which periods the instrumented trucks collected relevant inter-vehicle distance data within the platoon, as opposed to the periods where they served as platoon leaders, collecting irrelevant data preceding the platoon.

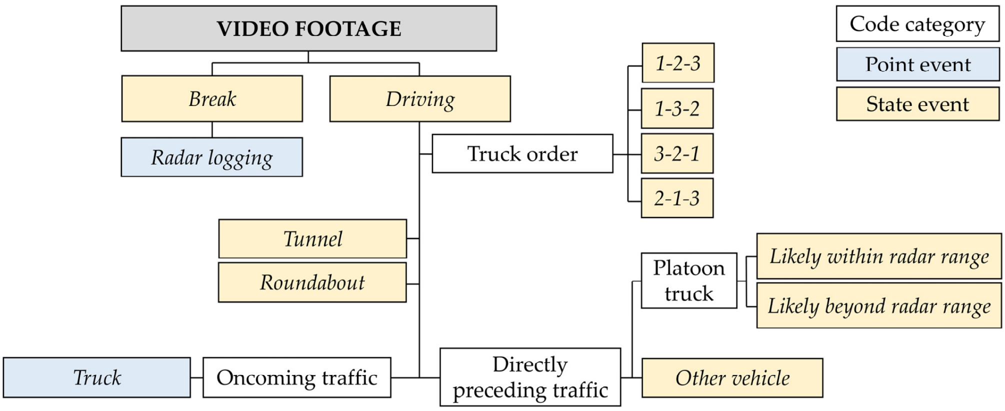

Figure 3. Overview of BORIS video codes.

The *Driving* video code in Figure 3 includes all conditions encountered, i.e., including tunnels and roundabouts, thus showcasing diverse, complex driving segments. See Table A5 in Appendix A.2 for its definition. *Tunnel* and *Roundabout* video codes denote scenarios of particular interest. In tunnels, inter-vehicle distances between the trucks cannot be determined using GNSS-based methods, and it is also unclear how tunnels affect operating conditions for the radar sensors. Roundabouts are demarcated areas (i.e., they are simple to code from video footage) with small horizontal radii, which can illustrate effects of road curvature on radar operation when the preceding truck turns. All events were coded separately for each truck. Tunnels were coded from the moment when the front of the truck in question entered the tunnel, to when the front of the truck left the tunnel. The same principle was used for roundabouts, i.e., coding the moment when the front of each truck entered and exited the circulating area.

Events were defined for visual inspection of the distance to (visibility of) the preceding truck, as the trucks were at times located far apart. The goal was to remove data from periods when the preceding truck was difficult or impossible for the sensor to detect, due to the driving situation. This occurred in two scenarios. Firstly, it occurred in sharp turns, where the preceding truck would disappear from radar field-of-view. Dashboard cameras had larger horizontal fields-of-view than radar sensors, so when no preceding vehicle appeared on camera, the radar would also not detect it. Secondly, it occurred when the trucks drove far apart. The distance range was shorter for radar than for the dashboard camera, which was only constrained by line-of-sight. Both scenarios were coded as *Likely* *beyond radar range (LBRR*). Conversely, *Likely within radar range (LWRR)* denotes driving periods when relevant radar data likely could have been collected.

The manual nature of this process introduces some limitations. Periods when the preceding truck was actually *LWRR* may have been coded as *LBRR*, and vice versa. Transitions between these codes may also occur at different distances. Albeit imperfect, this categorization is preferable versus including all radar data, even when the preceding truck was located far beyond radar range. For the far-apart scenario, centerline road markings initially aided the visual estimation. On rural roads with 80–90 km/h speed limits, these markings have standardized lengths and gaps totaling 12 m, which repeat continuously, cf. pp. 22 in the Norwegian road marking design manual [36]. After having coded *LWRR* and *LBRR* using road markings for some time, the remaining dashboard camera footage was coded without conscious reference to the road markings. It was also attempted to use pixel counts of the preceding truck for this purpose, but doing so at large scale was unsuccessful. An overview of the data collection and processing steps is provided in Table 1. See Table A5 in Appendix A.2 for examples of video codes.

Table 1. Overview of the data collection and processing steps.

Step	Context	Description
1	Equipment start-up and logging	Start GoPro-cameras successively, while, for each camera, presenting local time on phone screen.
2		Start radar logging script while producing loud verbal cue.
3	Data collection	Platoon driving.
4	Equipment logging stop	Stop GoPro camera recordings successively. Stop radar logging.
5	Data transfer	Import GoPro video files and raw radar files to computer.
6	Synchronize GoPro videos with each other	For each truck: Synchronize GoPro video footage in BORIS, using offset values. Synchronization is based on the difference between local time presented to each camera upon starting the recordings, and fine-tuned using recorded audio.
7	Synchronize GoPro videos to local time	Define *Date and time* in BORIS observation equal to the local time shown to the reference camera (i.e., the longest video file) by the phone application when the reference recording was started.
8	Video coding	Code *Radar logging* based on visual and verbal cues from interior camera. Code remaining events from dashboard camera footage.
9	Synchronize radar data to local time	Export events list for each observation to spreadsheets.
10		Apply datetime shift to radar timestamps based on *Date and time* for each BORIS observation to match them with *Radar logging* events.
11	Radar data curation	Radar data were curated using six filters.

2.4. Radar Data Processing

Video coding events were exported from BORIS as spreadsheets, and the *Date and time* from the corresponding *observation* was added to the timestamp of each instance of the *Radar logging* video code. This assigned local time to the instance when radar logging was started, and served as basis for synchronizing video codes and radar data in Python.

Filters were needed to extract only the inter-vehicle distances between the platooning trucks. Filtering aimed at removing data from periods when the trucks were not driving (i), data which did not correspond to the preceding truck (ii), noise (iii), and finally, data from periods when the preceding truck was outside sensor range (iv).

Timestamps, distance (m), relative velocity (km/h) and signal-to-noise ratio (decibel, dB) were logged, for up to five simultaneously detected targets. Positive relative velocities corresponded to targets receding from the radar, and negative relative velocities corresponded to approaching targets. For the curated radar dataset, an example of the former would be the preceding truck accelerating away from the truck in question. Conversely, the preceding truck decelerating would be an example of the latter. SNR denotes the ratio of the signal power to the noise power. Larger and more reflective objects will produce measurements with higher SNR values. The radar data were curated using successive filters, cf. Table 2. The following paragraph outlines the details and purpose of each filter.

Table 2. Overview of radar data filters.

Filter	Description
1	*Driving* and *following*
2	Relative velocity within ±30 km/h
3	Signal-to-noise ratio < 15 dB
4	Target selection
5	Downsampling 1 Hz
6	*Likely within radar range* (*LWRR*)

First, the *Driving* video code was used to remove data collected during irrelevant periods. It discards data from *Break* periods, so only data from *Driving* periods remain. Simultaneously, truck order codes were used to exclude radar data collected during periods when each truck served as platoon leader. Specifically, radar data from truck 2 stem from the driving periods with truck orders *1–2–3*, *1–3–2* and *3–2–1*, while radar data from truck 3 stem from periods coded as *1–2–3*, *1–3–2* and *2–1–3*. Data were discarded from periods where external vehicles (*Other vehicle*) preceded each respective truck.

Filters for relative velocity and SNR (filters 2 and 3, respectively), were used to clean the remaining data. Relative velocities were explored in histograms, shown in Figure 4a. Some relative velocity bins were far more frequent than others, giving the dataset large dynamic range. The vertical axis is logarithmic, magnifying bins with few measurements.

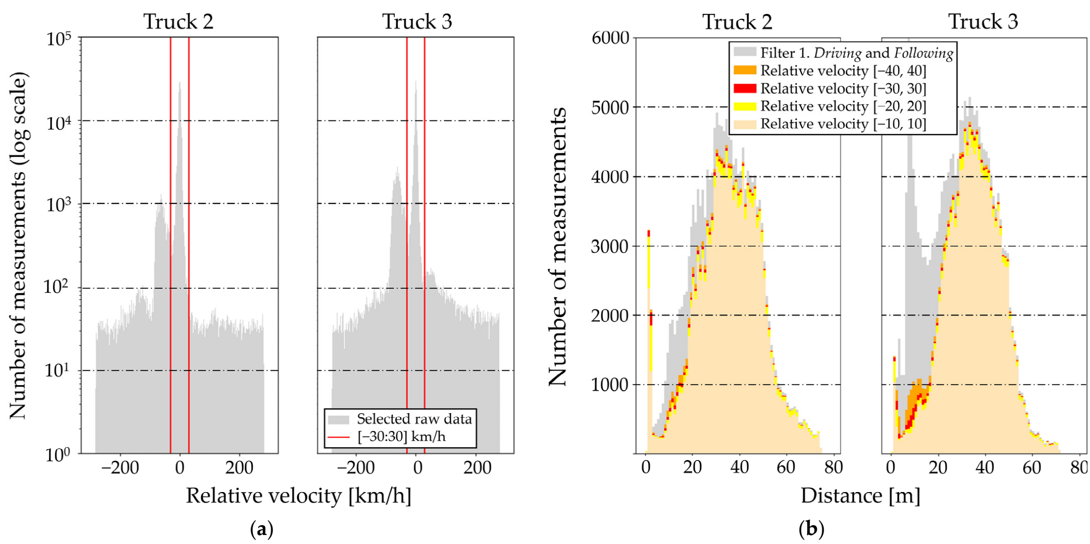

Figure 4. (**a**) Relative velocity histograms. (**b**) Distance histograms with relative velocity filters.

The histograms show two data spikes. Relative to a forward-facing sensor mounted in a moving truck, stationary surroundings have negative speed comparable to the speed of the truck. Assuming traffic moves at the speed limit, oncoming vehicles are measured with negative relative velocities at twice the speed limit. Similarly, measurements from the preceding truck have relative velocities fluctuating around 0 km/h. These two clusters of relative velocities appear as vertical spikes in Figure 4a. The cluster from the preceding truck was the largest. This is as expected in car-following situations, which necessitate continuous acceleration and deceleration [37]. The smaller clusters in Figure 4a had an order of magnitude fewer measurements, all of which had relative velocities in the −30 to −160 km/h range. They included static objects, oncoming traffic and measurement noise. Thus, for the relative velocity filter (filter 2), choosing −30 km/h as the lower threshold was natural, placing it at the local minimum between the spikes. Similarly, setting the upper threshold at +30 km/h made it so the entire top spike was included, while minimizing the inclusion of measurements from the noise floor.

As shown in Figure 4b, the radar data were also subjected to different relative velocity filters, starting at ±40 km/h, successively constricting by ±10 km/h steps until the narrowest filter of ±10 km/h. The color of each filter reflects remaining data points *after* that filter has been applied. For instance, remaining data after relative velocity filtering at ±30 km/h are shown in red. The ±40 km/h filter left a spike from 10–20 m for truck 3. The ±30 km/h filter removed most of the spike, and subsequent filter constriction did not cause notable differences. Thus, ±30 km/h was chosen, striking a balance between retaining most measurements corresponding to the preceding trucks and minimizing unwanted ones (oncoming and stationary objects), while including situations with sudden braking and acceleration in the platoon, which are perhaps the most interesting ones from a safety and fuel savings perspective. The radar sensors were listed as having a velocity accuracy of ±0.25 m per second. At ±30 km/h cut-offs, this amounts to a possible deviation of 3%, which is considered acceptable.

Still, as shown in Figure 4b, relative velocity filtering did not remove the leftmost spikes of measurements at distances too short to represent the preceding truck (0–5 m). Since the platoon drove with 2–3 s gaps, these do not represent the preceding truck. Calculations using Equation (A1), based on the 30° vertical field-of-view of the sensor, show that the road can be detected at 8–8.5 m forwards, meaning further away than the spikes. Thus, they are most likely clutter due to roadside detections, such as such as rock faces, tunnel walls, guardrails and signposts. Compared to the large, reflective rear walls of preceding trucks, such measurements should presumably be noisy, i.e., have small SNR values. Conversely, if these measurements did originate from the preceding truck, they should have had large accompanying SNR values. SNR values at short distances were indeed found to be small, and filtering for SNR < 15 dB was successful in removing them. As shown in Figure 5a, 15 dB filtering fell at a local minimum or saddle point between two distinct SNR data spikes. The data were also subjected to different SNR filters, illustrated in Figure 5b, but the filter was not constricted further, as doing so caused removal of data points with distance values around 40 m, likely corresponding to the preceding truck.

Since the radar sensors were able to measure up to 5 detections simultaneously, the next filter (filter 4) involved selecting only one desired target in multi-target instances: The one most likely corresponding to the preceding truck. The distance value of each detection was compared with the average distance values of the previous 10 measurements (moving average). The detection with the smallest difference was chosen. However, occasional single-object detections had distances which were quite different from the general trend. In such cases, the algorithm had no choice but to select the only detection available. This produced spikes or drops in distance which affected the moving average. This problem was subsequently minimized by filter 5, which downsampled the data to 1 Hz (one measurement per second) by averaging all distance measurements within each second. This temporal resolution was considered sufficient, and also allowed for direct coupling between curated radar data and event durations from video footage.

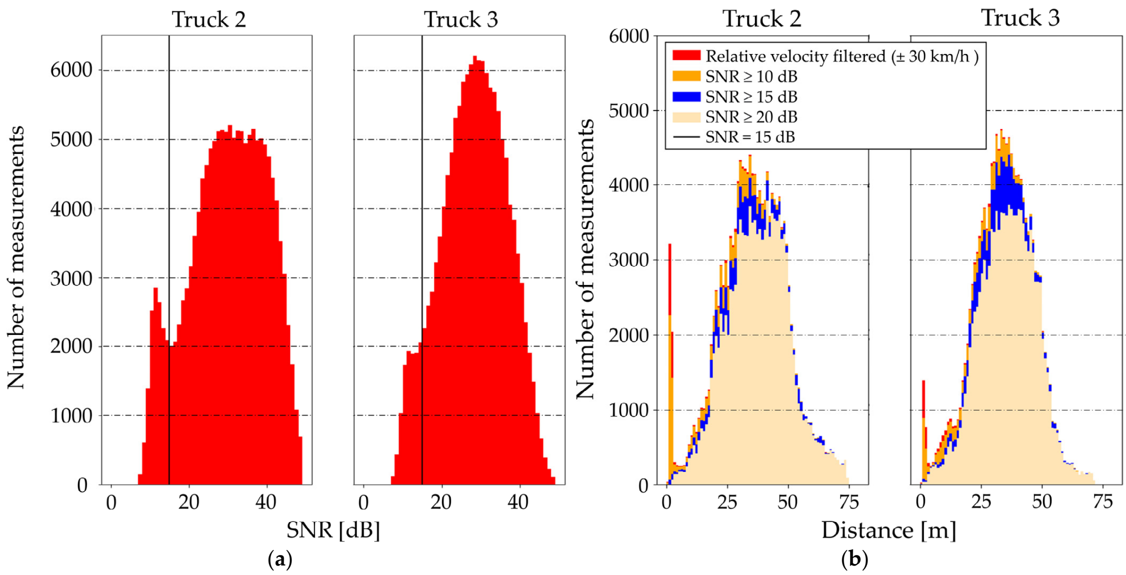

Figure 5. (**a**) SNR histograms after relative velocity filtering. (**b**) Distance histograms with different SNR threshold (after relative velocity filtering).

Inspecting plots of distance versus time for downsampled radar data revealed the presence of sporadic periods entirely void of points, and also to periods when points were scattered (i.e., having varying distance values following no obvious trend). To understand these detections, video footage was coded for *LWRR* and *LBRR*. Filter 6 used these codes to include only data collected in *LWRR* periods, and to exclude data collected during *LBRR* periods. Cameras malfunctioned at times, during which *LWRR* and *LBRR* could not be coded. Associated radar data were discarded, ensuring methodological consistency.

In brief, filters 1 and 6 were based on manual video codes, while filters 2 and 3 were based on recorded radar metrics, making them the most interesting ones in terms of radar operation. Filters 4 and 5 were computational heuristics. See Appendix A.3 for more details.

3. Results and Discussion

This section explores effects of the filtering process, before discussing differences between expected and empirical maximum distance ranges. It also explores the ability of the sensors in measuring the preceding truck in different driving situations. Finally, suggestions for future work are made. See Appendix A.4 for complete data tables.

3.1. Impacts of Filtering

Impacts on the number of data points are detailed, before discussing the effects on recorded metrics: relative velocity, signal-to-noise ratio and distance.

Figure 6 shows the sizes of datasets as a function of the filtering steps. The datasets of trucks 2 and 3 were affected similarly. Downsampling (filter 5) included a mean of six data points and a mode of seven. Figure 7 is a distance histogram showing the effects of all filtering steps. Note how early filters mostly remove measurements at close distances.

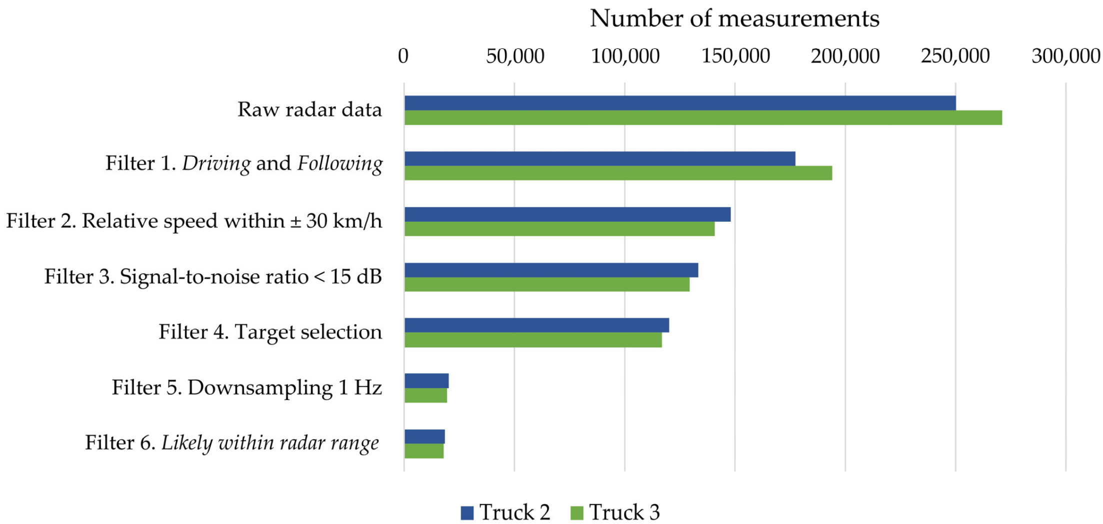

Figure 6. Number of measurements after each filtering step has been applied.

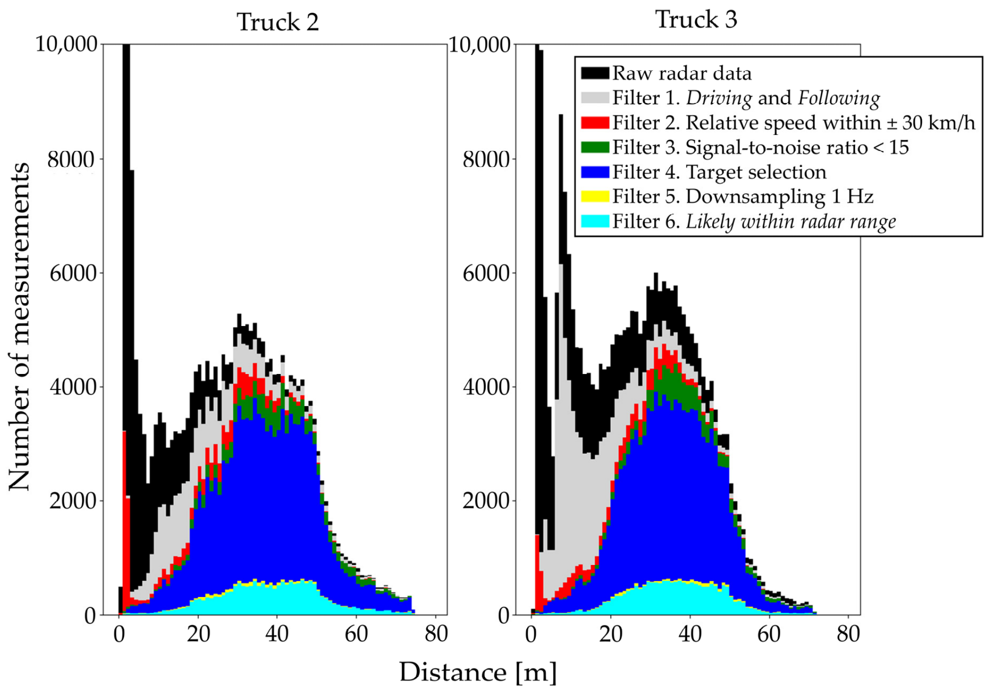

Figure 7. Histogram of measured distances as a function of filtering steps.

3.1.1. Relative Velocity

Overall, filtering reduced relative velocity data spread. Still, filter 1 increased relative velocity and data spread for trucks 2 and 3. In breaks, trucks were parked behind one another. Thus, removal of data from break periods serves to increase data spread, since these metrics differed more in driving periods. Excluding filter 1 (*Driving* and *Following*), filter 2 (relative velocity $\pm$ 30 km/h) affects the measured relative velocity the most, by removing data points corresponding to oncoming vehicles. This filter also reduced the average relative velocity to approximately −0.5 km/h for both trucks. Thus, while average relative velocities approach zero (as they should in car-following situations), they remain slightly negative. The negative value is due to most detected objects (with the exception of the preceding trucks) heading toward the sensors (as opposed to receding from them). The curated datasets for both trucks had slightly more instances of negative than positive relative velocities. The impact of filter 2 is greater for truck 3 than for truck 2, despite both having approximately equal sizes of datasets. It removes 20% of measurements from truck 3 and only 12% from truck 2, versus the number of measurements remaining after filter 1. In fact, the dataset of truck 3 enters filter 2 with a larger average relative velocity, presumably due to platoon instability and weight differences in which perturbations caused harsh braking for truck 3, which would naturally tend to occur at short distances, which filter 2 ended up removing (cf. Figure 7). Subsequent filtering steps slightly reduce the variability of relative velocity measurements, suggesting that erroneous detections are gradually removed.

3.1.2. Signal-to Noise Ratio (SNR)

Filtering caused average SNR to stabilize around 29–32 dB for all trucks. Overall, filtering decreased SNR data spread. The minimum SNR was only affected by filter 3 (SNR < 15 dB). As intended, filter 3 subjected the data to a step-change, starting at 6.7–6.9 dB and ending up for all three trucks at 15.1 dB. The effects of each filter gradually diminish. Interestingly, all trucks measured different maximum SNR values, which were reduced in filter 5 (downsampling). As shown in Figure 5b, SNR filtering worked as intended by removing measurements at short distances.

3.1.3. Distance

Distance was the only recorded metric which was not used as a basis for filtering. Average inter-vehicle distance values, shown in Table 3, suggest that truck 3 drove closer to its preceding truck than what truck 2 did. This was visually confirmed from video footage. After curation, average values were 38.6 and 36.1 m, for trucks 2 and 3, respectively. Still, distributions of distances appear to differ somewhat, with spikes at 0–10 m for truck 2, and 10–20 m for truck 3.

Table 3. Distance metrics (in meters) after each filtering step.

Filtering Step	Truck Number					
	2			3		
	Average	**Maximum**	**Standard Deviation**	**Average**	**Maximum**	**Standard Deviation**
Raw	26.5	74.4	17.6	25.2	71.5	15.9
1	33.5	74.4	14.8	29.3	71.5	14.5
2	35.5	74.4	14.3	34.4	71.5	12.3
3	37.4	74.4	13.0	35.5	71.5	11.5
4	37.2	74.4	12.9	35.3	71.5	11.5
5	38.2	74.3	13.0	36.1	71.4	11.5
6	38.6	74.3	12.9	36.1	71.4	11.3

Unfiltered maximum distance values for trucks 2 and 3 were 74.4 and 71.5 m, respectively, and were virtually unaffected by filtering. Only filter 5 (downsampling) reduced maximum distances, and only by 0.1 m in both cases. This resulted in curated maximum distances of 74.3 and 71.4 m. While distance ranges were never systematically tested, maximum distance values may be used as a proxy. While driving on straight road segments, inter-vehicle distances oscillated. The trucks would occasionally drive closely together before becoming dispersed, travelling with spacing between the trucks so large that each preceding truck was eventually located beyond sensor range. Thus, for each truck, measurements should exist at the radar range boundary. As stated, filter 6 (*LWRR*) did not further reduce maximum distance values than what filter 5 did. Figure 7 shows that filter 6 did not further reduce maximum distance values since it had little effect beyond approximately 50–55 m. Since *LWRR* video coding was carried out visually, somewhat imprecisely, the farthest radar measurements still tend to appear in *LWRR*-filtered data. Had it been more precise, maximum distance values following filter 5 would best represent *actual* upper sensor ranges.

The aforementioned maximum distance values for trucks 2 and 3 fall short of the theoretical ranges 75.0 and 73.1 m by 0.9% and 2.4%, respectively. Hence, both sensors appear to underperform slightly versus expected ranges, but still fall within the estimate provided by the supplier. The deviation is smallest for truck 2. Since the datasets from both trucks are otherwise comparable, the chosen parameter values N_s and f_0 for the radar sensor in truck 2 appears to be preferable. Future testing could explore this.

For the curated radar data, average relative velocity and average SNR were inspected as a function of inter-vehicle distances. For both trucks 2 and 3, these metrics were calculated within successive 10-m distance bins. The lower bin was 0–10 m, and the upper bin was 70 m and above. For all bins, average relative velocities fell within the error margin of the sensors. On the other hand, average SNR values are more interesting. For all bins, average SNR very seldomly fell below 30 dB, and remained high even at long distances, indicating that the radar cross-sections of the preceding trucks are sufficiently large to allow for longer detection ranges, cf. Tables A8 and A9 in Appendix A.4. Thus, parameters could likely have been chosen to achieve a maximum range approaching, and perhaps even exceeding, 100 m. The radar user manual illustrates that cars can be detected at 75 m, while buildings can be detected at 100 m. Due to the size of the truck rear walls, they may provide 'building-like' detection ranges. This study tracked large, reflective metal back walls of semi-trailers, with cross-sectional areas exceeding 8 square meters. The back walls of semi-trailers are larger than those of other vehicles and presumably facilitate higher-quality detections. Measuring distances to smaller vehicles should be tested. While the maximum distance range may be greater when detecting trucks than passenger cars, situations may exist where trucks are less favorable. For instance, when traversing sharp curves at short distances, the radar cross-section changes as truck back walls change angles in relation to the sensors, as opposed to being located perpendicular to them. Some military ships and aircraft are deliberately made from planar surfaces joined at sharp angles to achieve radar stealth. Similarly, truck back walls are also two-dimensional planar surfaces. In curves, reflected signals may scatter away from the receivers and cause data loss. This may also occur if the preceding truck is located outside the main lobe of the radar antenna. Such diffraction effects were reported in [38].

3.2. Radar Sensor Operation in Different Driving Situations

The curated radar data were coupled with video codes to determine whether the sensors captured high-quality inter-vehicle distance measurements when they should have been able to. Filter 6 aimed to remove periods when respective preceding trucks were located beyond radar range. We now check whether the radars were able to account for the remaining duration. *Driving* is explored, and also *Tunnel* and *Roundabout* subcategories.

Outputs from filter 6 contain radar data at 1 Hz, so aggregated video code durations (in seconds), when filtered for *LRWW*, are directly comparable to curated radar data. The proportions are shown in Table 4. Both sensors retained a similar number of measurements in each condition. As Table 4 shows, the sensors detected the preceding truck in most situations where it had the opportunity to do so. Using *Tunnels* to illustrate: Trucks 2 and 3 drove in *Tunnels* while having their respective preceding trucks within radar range (*LWRR*) for approximately 26 min (1647 and 1688 s, respectively). Aggregated over these same periods, their radar sensors outputted 1576 and 1609 curated measurements (at 1 Hz) after filter 6. As proportions, this yields 96% and 95%, respectively. Examples from each condition are shown in Table A5 in Appendix A.2.

Table 4. Proportions of curated radar data retained vs. *LWRR*-filtered aggregated event durations.

Condition	Trucks	
	2	3
Driving *	85%	83%
Tunnels	96%	95%
Roundabouts	88%	89%

* *Driving includes Tunnels and Roundabouts.*

Radar data and video codes can be used to visualize and explore excerpts of curated radar data (*LWRR*) from different driving intervals. Inter-vehicle distances are plotted versus time. Excerpts indicate large variability in inter-vehicle distances as a function of infrastructure type and road standard, as suggested in [23].

Since *Tunnel* and *Roundabout* video codes have non-zero durations, a choice had to be made regarding from which truck to visualize them. Truck 2 was chosen, being the middle truck in the platoon for 88% of the drive. Note that, at the time resolution used (1 min divisions), the difference would have been negligible if visualizing codes from one of the other two vehicles. Oncoming trucks seemed to cause the platoon to slow down, which also affected inter-vehicle distances, particularly on narrow roads and in sharp curves. Therefore, *Oncoming truck* video codes are shown. Being point events, these could be visualized for each truck separately. The horizontal axes (d hh:mm) were not fixed, so excerpts have slightly different durations (between 5 to 10 min). As the field study took place over two days, d-values are either 1 or 2.

3.2.1. Visual Verification of Maximum Range

Figure 8 shows three excerpts from *Driving*. While no tunnels or roundabouts are shown, statistics from this category in Table 4 also include those durations, thus showcasing diverse, complex driving segments. While serving as followers for 7 h, trucks 2 and 3 drove with their respective preceding trucks within radar range for approximately 6 h. All excerpts in Figure 8 had the preceding truck within range, so trends for measured distances appear mostly continuous. The top excerpt stems from an old, narrow road section without centerlines. Trucks often adjusted their speeds, including when encountering opposing trucks, as revealed by reduced inter-vehicle distances. The middle excerpt stems from the traversal of a flat and wide high-quality road with a 90 km/h speed limit and gentle horizontal curves. Here, the trucks maintained constant distances over long time periods, and opposing trucks did not influence the platoon. The individual data points from truck 2 which are located below the general trend were chosen by the algorithm since the sensor did not detect other data points during that logging instance. In general, truck 2 had more such erroneous measurements than truck 3 did, but it is unclear why this is the case. The lower excerpt illustrates the descent of a challenging mountain pass (negative 6% gradient), where trucks 2 and 3 reduced their speed repeatedly, to avoid speeding and becoming located too close to their respective preceding truck. These excerpts suggest that truck platooning is more suitable on wide, modern roads than on old roads with adverse horizontal and vertical alignment.

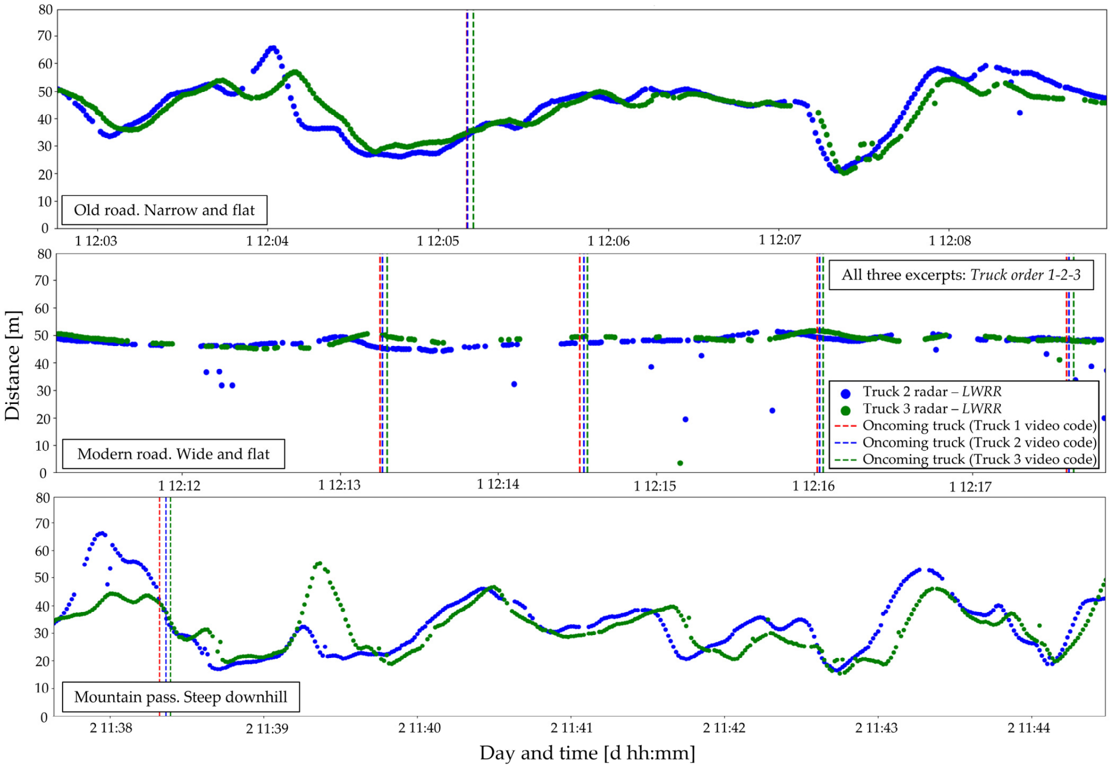

Figure 8. Inter-vehicle distances measured from three separate driving excerpts, *LWRR*, during which radar range was never exceeded.

Figure 9 shows three excerpts during which, for both trucks 2 and 3, the inter-vehicle distance appears to have occasionally exceeded maximum radar ranges. Blue (truck 2) and green (truck 3) horizontal lines illustrate the farthest distances detected, which differ somewhat between excerpts. Nonetheless, for radar sensors in trucks 2 and 3, respectively, the maximum distances are approximately 75 and 70 m, which support the aforementioned statistics-based radar range estimates. The three excerpts stem from two different mountain passes. The two upper excerpts correspond to traversal of Mountain pass A, with very difficult combinations of sharp horizontal curves and vertical gradients. Videos were also useful in inspecting the radar data after curation. The combination of long inter-vehicle distances and horizontal curves occasionally caused the preceding truck to be obscured by rock walls at the inner part of right-turn curves (pale shading). Mountain pass B, shown in the lowermost excerpt, was more forgiving in terms of road alignment.

In the upper excerpt, the data from truck 3 (green) at timestamp 16:56 potentially reveals the presence of a phenomenon which, together with the high average SNR values measured at large distances, suggests that sensors are capable of measuring the preceding truck far away. It appears as if measurements which naturally belong to the top of the green curve are folded down, instead of occurring at 90–100 m, where extrapolation would place them. Thus, it looks like the radar in truck 3 does measure the preceding truck, despite it being located beyond the maximum range imposed by the chosen parameters. Stated otherwise, the radar appears to measure points beyond its unambiguous range, referring to the maximum distance a target can have while it can be guaranteed that the reflected pulse from that target corresponds to the most recent transmitted pulse [14,39]. At this timestamp, it appears as if the returned signal is associated with the wrong transmitted pulse, so the range becomes ambiguous. Filtering for *LWRR* and *LBRR* served to remove most durations where such long-distance samples may have been folded into the ambiguous range. However, the manual video coding process did not remove all such instances. The presence of folding may have influenced distance metrics to the downside.

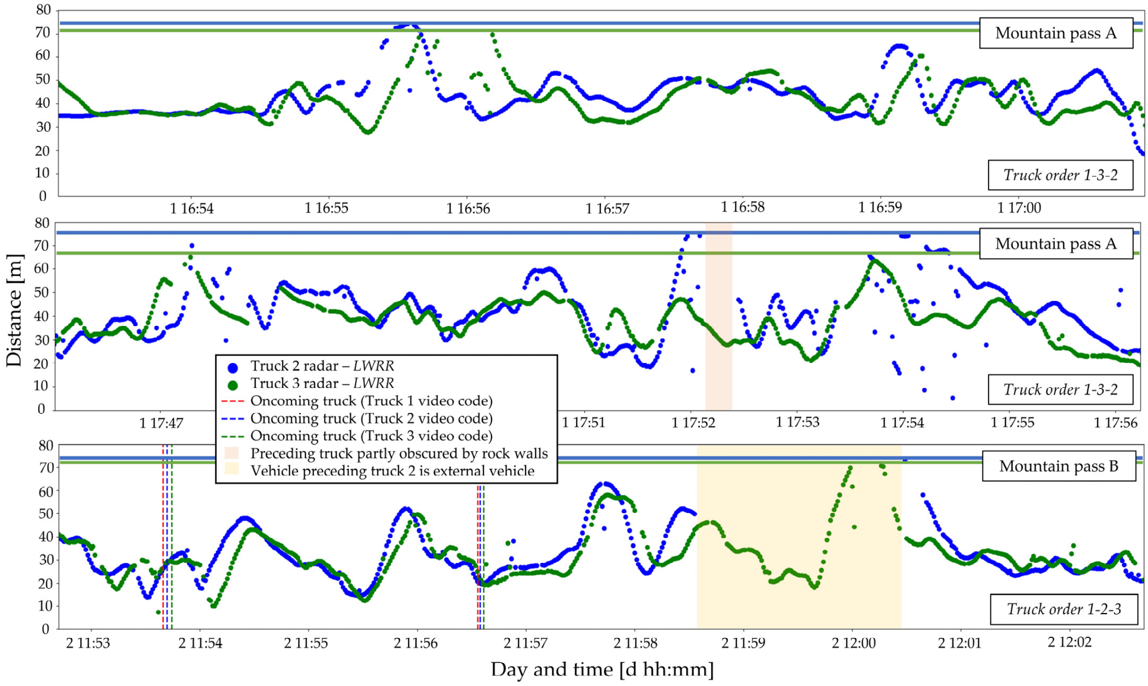

Figure 9. Inter-vehicle distances measured from three separate driving excerpts, *LWRR*, during which radar range was exceeded. Horizontal lines show farthest measurements.

Data from truck 2 in the middle excerpt of Figure 9 are noisier than for all other excerpts shown, but it is unclear whether the folding phenomenon occurs here. The outage for truck 2 in the lower excerpt stems from a period when a passenger car partly overtook the platoon, being sandwiched between truck 1 and 2 until also overtaking the lead truck. Data from such periods were removed by filter 1 (*Driving* and *Following*).

3.2.2. Tunnels

It is unclear how tunnels affect the ability of the sensors to measure inter-vehicle distances. Tunnels may reduce operational complexity, as rock walls cause peripheral narrowing of roadside areas. However, walls, lighting and ventilation elements may introduce clutter. Such features are less frequent on roads in natural terrain.

All *Tunnel* driving occurred in truck order *1–2–3*. Figure 10 shows excerpts from six representative *Tunnel* traversals (green shading). Driving periods outside tunnels have white backdrops. All excerpts were coded as *LWRR*, except for the period between the two tunnels in the top excerpt, when data were lacking for truck 2. This period was coded as *LBRR*, as truck 1 was located far away. Comparing Figures 8 and 10, it seems as if filter 4 (target selection) chooses erroneous data points at comparable frequencies both inside and outside tunnels. Thus, tunnel driving does not appear to degrade radar operating conditions. In tunnels, maximum distance values for trucks 2 and 3 were reduced by 8–9%, and the distance standard deviation dropped by 18% and 15%, respectively. Thus, inter-vehicle distances were moderated by *Tunnels*, causing closer, more uniform driving at lower speeds. This made preceding trucks occupy a larger part of radar the field-of-view. However, measurements collected in tunnels were noisier than those collected during *Driving*, indicated by lower SNR values (weaker signal). For both followers, *Tunnel* filtering reduced mean SNR by 3%, maximum values by 6–8% and standard deviations by 7–11%. This did not affect the curated radar data when plotted: In Figure 9, erroneously selected targets in tunnels appear to have distance values at similar deviations to the trend, compared to erroneously selected targets outside tunnels. Thus, it appears as if inter-vehicle distance measurements between platooning trucks are not adversely affected by tunnels.

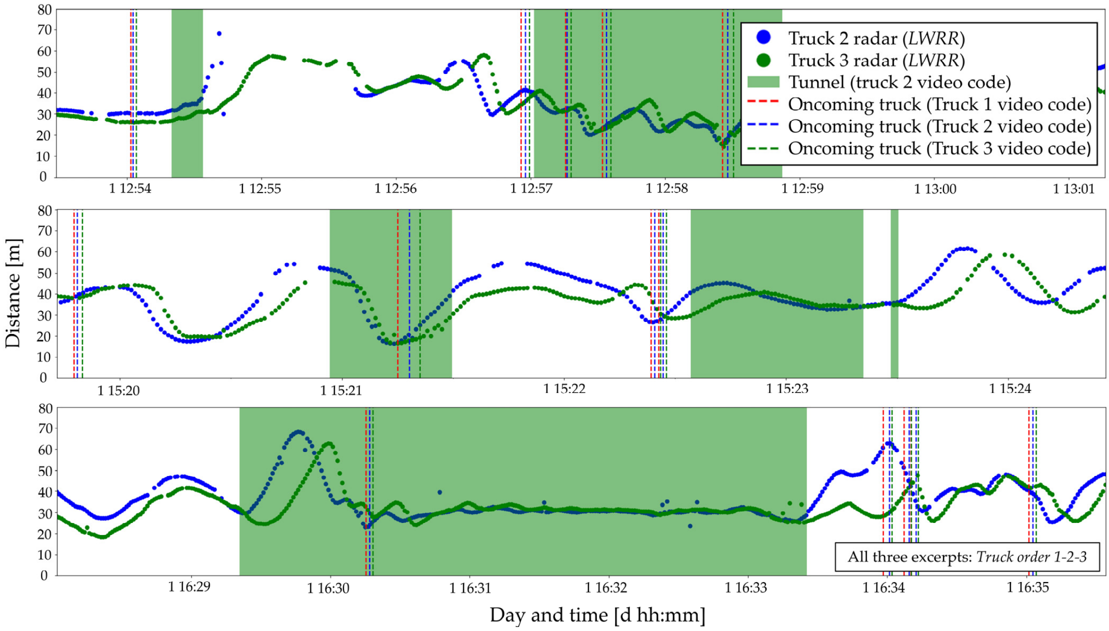

Figure 10. Radar data for three separate truck driving excerpts, *Tunnel* and *LWRR*.

3.2.3. Roundabouts

Roundabouts may allow for exploring the effects of sharp road curvature on radar operation. Most roundabout traversals involved straight movements, encountering little to no traffic. Figure 11 shows excerpts from five traversals (pale red shading), all of which occurred in truck order *1–2–3*. Driving periods outside roundabouts have white backdrops. The first traversal in the middle excerpt involved trucks 1 and 2 performing a full revolution to get rid of external vehicles located between trucks 2 and 3. Truck 3 had *Other vehicles* preceding it before entering this roundabout, so its data were removed by filter 1. The traversal in the lower excerpt involved all three trucks revolving one round. Trucks 2 and 3 both had 10 traversals as followers, with 5 straight, 1 left turn and 4 right turns. For both trucks, only half of the aggregated *Roundabout* durations had the preceding truck within field-of-view, and even when accounting for field-of-view, 11–12% of data are lost. Figure 11 shows that data points retained in roundabouts generally have scattered distance values which are too large to represent the preceding truck. Sharp curve radii and limited antenna beam width resulted in lost field-of-view to the preceding truck, so radar sensors detected irrelevant objects until field-of-view was regained after the turn.

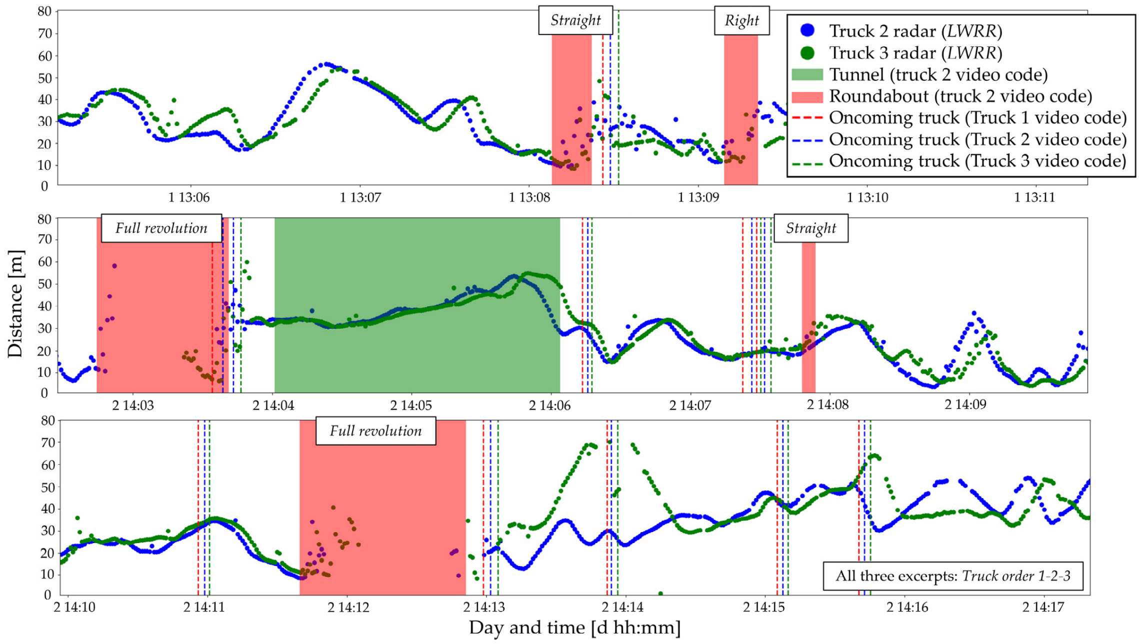

Figure 11. Radar data from three separate driving excerpts with *Roundabouts*, *LWRR*.

Average SNR values were 30 and 32% lower for trucks 2 and 3 in *Roundabouts* than for *Driving*, respectively, so the radar sensors detected noisier data. Proportions of radar data as a function of *LWRR*-filtered *Roundabout* durations (88–89%), are greater than for *Driving* (83–85%). This is likely due to the trucks being grouped closer together when traversing *Roundabouts*. Speeds were also lower, causing smaller inter-vehicle distances and greater spatial concentration of measurements. For trucks 2 and 3, mean distances were 66–62% shorter during *Roundabouts* than during *Driving*. The exploration shows that preceding trucks are tracked poorly when the platoon passes through roundabouts.

3.3. Suggestions for Future Work

This study explored the extent to which uRAD radar sensors could capture inter-vehicle distances during truck platooning. Several suggestions have been identified.

First, mode 4 (7 Hz) might be more suitable than mode 3 (13 Hz). As data were downsampled anyway, the trade-off between higher update rate (mode 3) and enhanced properties for ghost target reductions in complex scenarios (mode 4) should be explored.

To simplify data collection, radars could be remotely engaged from escort vehicles. If field trials are undertaken in areas with adequate cell coverage, virtual network computing (VNC) could be used to remote control all Raspberry Pi microprocessors. Radar data may also be visualized and coded in real-time. Future work may validate the radar data against GNSS positions, if undertaken in areas with good conditions for GNSS receivers. The performance of the sensors should also be compared against a known baseline, i.e., radars with known characteristics, such as those listed in [14], in controlled environments.

The cross-sectional signature of the trucks was not measured, and scattering effects were not explored. If present, such effects would be reflected in SNR values if systematically inspected at equal distances while varying the angle of the back wall of the preceding truck, resembling the set-up in [40]. Windshield attenuation effects were also not studied.

Synchronization of videos and radar data, and the subsequent process of video coding, worked well. However, both should preferably be automated, to reduce post-processing efforts and related human errors. Traffic and infrastructure events may be identified directly from radar data. Herein, tunnels and roundabouts were coded from the moment where each respective truck entered them, and to the moment when each respective truck left them. Later, video codes were overlaid on the radar data collected from each truck. However, since radar data shows the *preceding truck*, this may have introduced a systematic error. Perhaps video codes from the preceding truck should have been used instead. For tunnels, this is not particularly problematic since tunnel traversals (with *LWRR*) had long durations (on average 1.1 min). Thus, entering and leaving the tunnel occupies a very small part of the total duration. For roundabouts, however, the preceding truck had often traversed $\frac{1}{4}$–$\frac{1}{2}$ of the roundabout before the truck in question entered it, and it was first coded. Distinctions may be made between the preceding truck being located beyond range, and it being located laterally beyond field-of-view, as these are different phenomena. All data points may also be given metadata for all relevant video codes, simplifying video inspections of interesting events in the data.

Statistical approaches may allow cut-off values for filters 2 and 3 to be chosen automatically. In the target detection step, distance filtering could also be considered, perhaps discarding data points with distances deviating significantly from the general trend. This may solve the problem of erroneous single-object detections. Established data filtering, target tracking [41] or clustering techniques [42–44] could also be used, alongside more computationally complex methods for annotating or labelling combinations of radar and camera footage, e.g., in [31,45], and perhaps also machine learning approaches [46].

At times, dashboard cameras malfunctioned due to power issues, totaling 6% of driving time, during which 10% of all radar data were logged. As it was not possible to determine whether the sensors had reasonable operating conditions in these periods, the data were discarded. Mitigations include redundant cameras and independent power supplies.

4. Conclusions

Anteral uRAD radar sensors for Raspberry Pi were tested for estimating inter-vehicle distances between trucks. Three trucks participated in a real-word platooning field study. Data from integrated sensors were unavailable. Comparable results were found from the sensors in the two rearmost trucks, suggesting that they are feasible for this use case. Data filtering involved a multi-faceted methodology. While also filtering based on relative velocity and signal-to-noise ratio, video footage allowed for removal of data from irrelevant periods, and for exploring sensor operation in roundabouts and tunnels. This would not have been possible without video footage. The curated radar data can be used to model expected fuel savings from truck platooning on specific types of roads and road features.

Sensor ranges were estimated at 74 and 71 m, i.e., slightly shorter than suggested by theoretical calculations. The sensors captured the preceding truck for 83–85% of the time when it was located within radar range. In tunnels specifically, 95–96% of driving time was accounted for, likely due to closer driving. Average SNR decreased 3% in tunnels, compared to all driving, but this did not appear to affect the accuracy of the target detection step. When turning in roundabouts, the field-of-view to the preceding truck was often lost, and the sensors detected their surroundings until field-of-view was regained after completing the turn, causing average SNR values to drop (30–32% lower). Straight movements in roundabouts were less problematic, as field-of-view was mostly retained.

High SNR values were observed at far distances, indicating that the sensors, with optimal parameters, may be capable of measuring preceding trucks further away. The findings suggest that simple, inexpensive radar sensors and action cameras can facilitate collection of inter-vehicle distance data from truck platooning field trials.

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Appendix A

The appendix is subdivided into four parts, providing background information and methodological details for reproducibility, alongside tables with results.

Appendix A.1. The Radar Sensors

Anteral uRAD radar sensors, version 1.1, were used alongside Raspberry Pi 4, model B with 4 GB RAM. Micro-SD cards (16 GB) were purchased, with the Raspberry Pi operating system and uRAD software pre-installed. Technical support was also purchased. Table A1 provides an overview of the radar configuration parameters. Testing prior to the field trial is outlined in Figure A1 and Table A2. Collected test data and corresponding camera footage were sent to the supplier, who proposed recommendations for future testing. Table A3 details the parameters which were used in the field study.

(**a**) (**b**) (**c**)

Figure A1. (**a**) Dump truck test set-up; (**b**) Back wall of preceding truck seen from cabin during driving, with radar sensor (yellow) and dashcam (red) circled; (**c**) Radar sensor side view.

The supplier detailed the pre-processing steps taken before sensors store data to memory: The radar transceiver chip receives the reflected signal. The mixer mixes the received (RX) signal with the transmitted (TX) signal, and outputs in-phase (I) and quadrature (Q) components at Intermediate Frequency (IF). These two analog I/Q IF signals go through a low-pass filter, an amplifier stage and a high-pass filter. Filter values are proprietary. Subsequently, the analog signal is digitalized with an ADC at 25 kHz in mode 1 and 200 kHz in modes 2, 3 and 4. In the digital domain, the complex signal is formed, FFT obtained, and from it, range, velocity and SNR of detected targets are derived. The supplier also stated that calibration by the user is not needed, as performance is controlled in the lab prior to shipment, by measuring a constant distance of 1.5 m in mode 2.

The combination of one Raspberry Pi attached to one uRAD radar board is here termed a *device*. The device was fixed to the interior of the windshield using a universal phone suction mount with a flexible arm, oriented such that the USB-C and micro-HDMI ports pointed directly upwards (cf. Figure A1). Since Raspberry Pi microprocessors were powered on and off using a USB-C cable, this orientation facilitated easy access and line of sight from above, for cable insertion and removal. It also made sure that the sensor did not detect the mount itself, being located outside radar field-of-view. Powerbanks and USB-C cables powered the devices at optimum voltage and amperage, while making data logging independent of truck power systems and status. This eliminated potential issues with undervolting and voltage spikes from in-vehicle outlets, while leaving flexibility for when logging start and stop had to be administered. Each Raspberry Pi had a Bluetooth USB dongle for a wireless keyboard and mouse, minimizing direct device contact. The dongle added an additional reason for ensuring stable power supply. The radar supplier confirmed that the dongle radio frequency would not affect radar operation. Along with the dongle, the micro-HDMI and power cables remained plugged into the device throughout the field trial. This allowed the devices to remain vehicle-mounted throughout both days, requiring only insertion and removal of the far-ends of the cables into the screen and powerbank for interfacing with the devices and powering them devices on and off, respectively. Radar output files never exceeded 5 MB, i.e., they were unproblematic with respect to SD card storage capacity. A battery powered portable monitor was used.

With 30° vertical fields-of-view, 15° swept down from horizontal, so vertical sweep became 75°, assuming sensors were mounted perfectly level. If trucks, with uRAD antennas at height h_a, traversed a constant gradient road section, the road would be detected at a distance, d, given Equation (A1):

$$d = h_a \cdot \tan(75^\circ) \tag{A1}$$

The presence of aftermarket dashboard tabletop surfaces required placing sensors at slightly different heights in each truck during the field study. With radar antennas at heights of 2.29 m (truck 2) and 2.15 m (truck 3), the road would be detected 8–8.5 m forwards. Having 30° fields-of-view also in the horizontal direction, radars also saw this far sideways at road level.

Table A1. Overview and discussion of uRAD radar parameters.

Parameter	Discussion
Mode	Of four modes available, only modes 3 (triangular) and 4 (dual-rate) measured both distance and velocity. Velocity would enable filtering away stationary and oncoming objects, to be left with desired inter-vehicle distance to the preceding truck. Modes 3 and 4 differed in upper distance range and update rate. Mode 3 had an upper distance range of 100 m, versus 75 m for mode 4. The supplier stated that the range would also depend on the target, meaning its radar cross-section: "(. . .) a person is detected up to 40 m. (. . .) a truck, that is bigger and reflects more, (. . .) will be detected [at] 70 m but probably (. . .) much farther. 100 m is not a limitation of the radar, [but] a guide (. . .) for very big targets." Mode 4 should reduce ghost target detections in multi-target scenarios, at the expense of reduced range.

Table A1. *Cont.*

Parameter	Discussion
Ramp start freq., f_0. Operation bandwidth, BW	Ramp start frequency, f_0, could be set as 5–195 for modes 2–4. Operation bandwidth, BW, meaning the frequency sweep used in modes 2–4, depends on f_0, and should be maximized, subject to Equation (A2), to increase accuracy and to distinguish closely located targets. For each radar, different values were chosen to avoid interference. $BW_{max} = 245 - f_0$ (A2) The f_0 parameter denotes the starting frequency of the waves emitted by the sensor. The sensor operates at a frequency bandwidth of 24.005–24.245 GHz, and f_0 values are defined (in MHz) to set the offset from the lower threshold.
Samples and ramp duration, N_s	N_s is the number of samples taken from the reflected wave to calculate distance and velocity. Highest update rate requires lowest possible N_s. However, a trade-off is needed, since BW and N_s determine maximum range, through Equation (A3). $Distance_{max} = 75 \cdot \frac{Ns}{BW}$ (A3) The N_s parameter serves two purposes. Firstly, it defines the duration of each wave ramp, and secondly, it outlines the sampling rate from the reflected wave, per ramp duration, which can be used to calculate output metrics.
Max. detected targets, N_{tar}	N_{tar} is the number of targets that the sensor detects, 5 being maximum. If detecting more objects, the sensor logs data for those 5 with highest SNR. N_{tar} was maximized, capturing most data and providing possibility for filtering unwanted objects later.
Maximum detection distance, R_{max}	For modes 2–4, R_{max} is the maximum distance below which targets will be detected. R_{max} artificially reduces the zone of interest, excluding targets beyond this distance, even if they have higher SNR than those within it. R_{max} was chosen as 100 for all sensors, as this would search targets within the entire range. When asked if the sensors would stay fixed on the preceding truck in horizontal curves, the supplier stated that manual antenna modification could double the horizontal FOV, to the detriment of upper detection range. No manual modifications were made. For vertical curves, the supplier cited that the road in front of the truck, which would be more visible in vertical sag curves, could reflect the signal, masking the preceding truck.
Moving target indi-cator, *MTI*. Movement detection, *Mth*	Moving target indicator (*MTI*) allowed for including data only from objects with motion relative to the sensor. *Mth* is only relevant when using uRAD as a movement detector, and was not used.

Table A2. Pre-trial testing of radar parameter configurations.

Pre-Test Steps	Parameters	User Experience	Supplier Modifications and Recommendations
1: Passenger car test with one radar sensor and standard graphical user interface (GUI) 	Mode = 2 f_0 = 45 BW = 200 N_s = 200 N_{tar} = 5 R_{max} = 100 MTI = 1 Mth = 1	• Preceding traffic recorded well. • Data written to the same file each time subsequent data collection is stopped and started. • Data are only written to file upon logging stop. Susceptible to data loss if equipment malfunctions. Cannot distinguish driving segments. • Epoch time format impractical and not human-readable.	• Switch off Mth, as it is not relevant for the application. • Replaced GUI with Python script for increased update rate. • Code rewritten to create new output files upon each logging start. • Output files are now named with "start logging time" in human-readable format. • Data are now continuously written to file during logging, as opposed to batch writing upon logging termination.

Table A2. *Cont.*

Pre-Test Steps	Parameters	User Experience	Supplier Modifications and Recommendations
2: Test with two dump trucks. Follower with dashcam and one radar sensor 	Mode = 2, 3 $f_0 = 45$ $BW = 200$ $N_s = 200$ $N_{tar} = 5$ $R_{max} = 100$ $MTI = 1$ $Mth = 0$	• The preceding truck was recorded well, except in curves and intersections. • Mode 3 is preferred over mode 2; makes it easy to filter away stationary objects and oncoming vehicles based on relative velocity. • Filtering distance values for relative velocity exceeding $\pm$ 20 km/h removes much noise.	• Field study involves three sensors, not one. • Finalized parameters were recommended to avoid interference, yet maximize sensor range.

Table A3. Radar parameter configurations.

Truck ID	Common Parameters	Specific Parameters
2	Mode = 3 BW = 200 MHz N_{tar} = 5 targets R_{max} = 100 m MTI = 1 (active) Mth = 0 (inactive)	f_0 = 5 MHz N_s = 200 samples
3		f_0 = 25 MHz N_s = 195 samples

Appendix A.2. Video Footage, Video Synchronization and Manual Video Coding

Low-resolution video (LRV) file segments were converted to the MP4 format and merged using free Bandicut software [47]. Merged videos were imported to BORIS version 7.12.2. LRV files were used, since original MP4 files were too large for BORIS to handle. LRV files were 864 by 480 pixels, while original files were 1920 by 1080 pixels, both with 60 fps frame rates. Conversion reduced the file size by an order of magnitude, while retaining sufficient video quality for coding. Table A4 shows two code definitions, while examples of state events are shown in Table A5.

Table A4. Examples of video code definitions.

Video Code	Definition
Driving (S)	*Driving* starts when the truck is fully inside the correct lane on the roadway, with the steering wheel turned straight. It stops just before the driver starts turning the wheel, with the intention of entering driveways, parking areas or stop pockets. Except during *Break* and periods of camera malfunctions, every other video code is coded only when *Driving* is also active.
Break (S)	All time that is not *Driving*, is defined as *Break*. This includes maneuvering in and out of driveways, parking areas and stop pockets.

Table A5. Examples of coded state events for radar data filtering.

Event	Illustrations	
Tunnel		
Roundabout (Left): Straight; (Right) Right-turn		
LWRR (likely within radar range)		
LBRR (likely beyond radar range)		

Appendix A.3. Radar Data Curation

Radar data post-processing was carried out in Python 3.10. The Python libraries Pandas, NumPy, datetime, Matplotlib and openpyxl were used. All radar data were extracted into a Pandas DataFrame. In multi-target scenarios, objects were placed successively within the DataFrame, by descending SNR. The DataFrame contained the following data columns: Time {*datetime*}, Distance {*float*}, Velocity {*float*}, SNR {*float*} and Object number {*int*}. Since radar timestamps did not correspond to local time, datetime shifts were calculated based on the previously corrected *date and time* of each *Radar logging* instance, and the *date and time* with which the radar output files were named (cf. Table A2). Datetime shifts were added to the Time column, correcting all measurements. All radar data were merged into one DataFrame and saved as a Pickle file prior to curation.

Filters 4 (target section) and 5 (downsampling) are illustrated in Figures A2 and A3.

Figure A2 shows a 7-min period for truck 2. Chosen targets are blue, discarded ones purple, and the moving average turquoise. Averaging across 10 loggings, instead of fewer, reduced noise in turbulent situations. Inspection of radar data, e.g., when traversing *Roundabouts*, showed that approximately 10 loggings were needed after the video code ended, for distance to the preceding truck to stabilize.

The presence of lone blue data points located away from the blue trend in Figure A2, shows that this algorithm may choose the wrong target. Erroneous selections are those data points which clearly suppress the moving average distance value. Figure A3 shows a 10-min excerpt of downsampled radar data (blue), alongside data after filter 1 (gray).

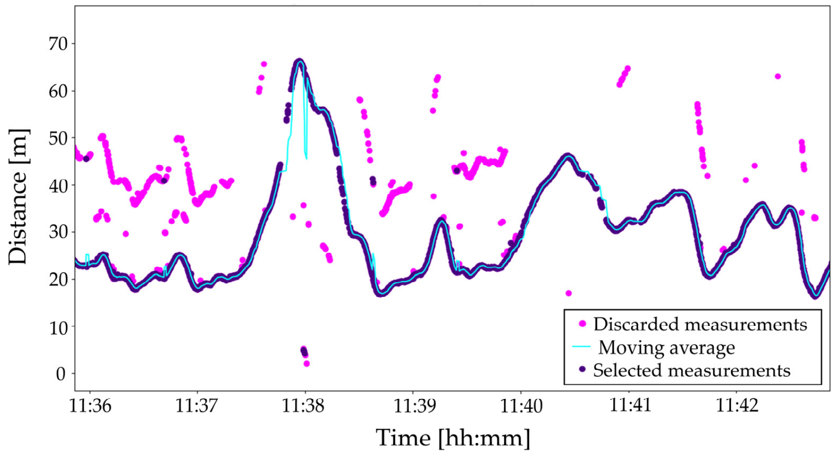

Figure A2. Truck 2 excerpt. Target selection when radar measures multiple objects simultaneously.

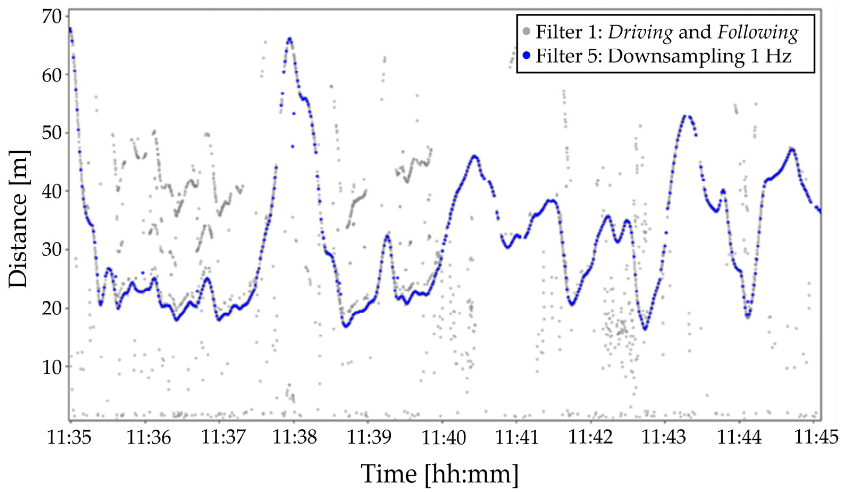

Figure A3. Truck 2 excerpt following filters 1 and 5.

Appendix A.4. Results and Discussion

Tables A6–A13 show statistics from each filtering step, the analysis of relative speed and SNR as a function of distance bins, and radar operation in different driving situations.

Table A6. Relative velocity statistics (km/h) for trucks 2 and 3 after each filtering step.

Filtering Step	Truck Number							
	2				3			
	Min	Avg	Max	Std	Min	Avg	Max	Std
Raw	−280.9	−5.7	281.0	40.4	−280.7	−9.4	280.7	45.9
1	−280.9	−7.7	281.0	43.7	−280.7	−11.3	280.7	48.9
2	−29.9	−0.5	29.9	5.5	−29.9	−0.5	29.9	5.5
3	−29.9	−0.3	29.9	4.8	−29.9	−0.3	29.7	4.6
4	−29.9	−0.2	29.9	4.4	−29.9	−0.2	29.7	4.2
5	−29.6	−0.2	28.6	4.3	−29.9	−0.2	27.2	4.0
6	−29.6	−0.1	28.6	4.2	−29.7	−0.1	27.2	3.8

Table A7. SNR statistics (dB) for trucks 2 and 3 after each filtering step.

Filtering Step	Truck Number							
	2				3			
	Min	Avg	Max	Std	Min	Avg	Max	Std
Raw	6.8	24.6	53.9	10.8	6.6	22.6	51.4	9.7
1	6.9	27.6	53.9	10.6	6.7	24.2	51.4	9.9
2	6.9	29.9	53.9	9.9	6.8	28.1	51.4	8.5
3	15.1	31.8	53.9	8.3	15.1	29.5	51.4	7.3
4	15.1	32.9	53.9	7.9	15.1	30.4	51.4	7.0
5	15.1	31.6	49.7	6.9	15.1	29.4	47.7	5.9
6	15.1	31.8	49.7	6.9	15.1	29.5	47.7	5.8

Table A8. Average relative velocity (km/h) and SNR (dB) for truck 2 as a function of distance.

Distance Bins	Avg. Relative Velocity (km/h)	Average SNR (dB)	# Measurements	% of Total
0–10	−0.4	30.0	204	1%
10–20	−1.0	32.3	1191	6%
20–30	−0.3	31.1	3327	18%
30–40	−0.1	31.8	5074	27%
40–50	0.0	32.4	5519	30%
50–60	0.2	31.4	2151	12%
60–70	−0.1	31.2	813	4%
70+	0.7	32.2	191	1%

Table A9. Average relative velocity (km/h) and SNR (dB) for truck 3 as a function of distance.

Distance Bins	Avg. Relative Velocity (km/h)	Average SNR (dB)	# Measurements	% of Total
0–10	−0.3	29.4	199	1%
10–20	−1.2	29.1	1113	6%
20–30	−0.4	28.6	4173	23%
30–40	0.0	29.0	5642	31%
40–50	0.1	30.2	4988	28%
50–60	0.0	31.0	1502	8%
60–70	0.9	31.6	270	2%
70+	0.4	31.4	29	0%

Table A10. Relative velocity statistics (km/h) for trucks 2 and 3 during *LWRR* and *Tunnel*.

Truck	Relative Velocity			
	Avg	Min	Max	Std
2	0.1	−19.7	28.6	3.5
3	0.1	−19.3	18.8	3.3

Table A11. Distance (meters) and SNR (dB) statistics for trucks 2 and 3 during *LWRR* and *Tunnel*.

Truck	Distance				SNR			
	Avg	Min	Max	Std	Avg	Min	Max	Std
2	36.4	10.6	68.2	10.5	30.8	15.1	46.9	6.4
3	36.2	13.8	65.0	9.6	28.5	15.7	44.0	5.2

Table A12. Distance (meters) and SNR (dB) statistics for trucks 2 and 3 during *LWRR* and *Roundabout*.

Truck	Distance				SNR			
	Avg	Min	Max	Std	Avg	Min	Max	Std
2	23.3	8.6	58.4	10.1	24.5	16.2	39.5	5.2
3	22.4	6.3	60.0	11.2	22.4	15.1	41.5	4.4

Table A13. Relative velocity statistics (km/h) for trucks 2 and 3 during *LWRR* and *Roundabout*.

Truck	Relative Velocity			
	Avg	Min	Max	Std
2	−6.5	−27.8	11.2	9.1
3	−5.9	−25.7	10.5	8.9

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Paper 3

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Operational and Infrastructure Readiness for Semi-Automated Truck Platoons on Rural Roads

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Abstract
On highways, truck platooning may reduce fuel consumption, improve road safety and streamline trucking operations. However, most roads worldwide are two-way, two-lane rural roads, i.e., conditions for which truck platooning should be tested to explore the extent of those advantages. This paper reports findings from a field study undertaken in Northern Norway, testing a platoon of three semi-automated trucks on rural roads with tunnels, mountain passes and adverse geometries. Fleet management and distance data, videos, interviews and conversations between participants were used to assess whether platooning was feasible on such roads. The platooning system was used without interventions through most road conditions, and worked well on flat and wide roads with 90 km/h speed limits. However, it struggled in sharp horizontal curves, where the following trucks would speed up before regaining connection to their preceding truck and then brake abruptly to regain the prescribed distance. Moreover, steep uphills were problematic due to inconsistent gear shifting between the trucks. Seemingly, no fuel savings were achieved, due to excessive following distances and suboptimal speed profiles on crest curves. To obtain further insights into the benefits of truck platooning on rural roads, we suggest redoing the field study with vehicle-to-vehicle communication, allowing for shorter following distances, and also performing a manual-driven baseline first.

Keywords: Truck platooning (1); field trial (2); rural roads (3); road geometry (4); tunnels (5).

Introduction
Truck platoons consist of virtually linked trucks that drive together in convoys with small headway distances [1], and are forecasted to be among the earliest commercially available use-cases of road vehicle automation [2]. Field studies are useful for assessing whether platooning can deliver real-world benefits [3]. Many have been undertaken, e.g., [4–8], though only on closed tracks and limited-access, multi-lane highways with forgiving horizontal and vertical geometry and ample space for overtaking. These studies show that truck platooning is feasible and has potential for further development. Benefits include lower fuel consumption

[1,2,9,10], improved traffic flow [4,11], reduced need for road expansions [9], improved safety [2,9], and, in the longer-term, lower cost through partly or fully driverless operations [2,12] which may also mitigate driver shortages [13].

However, many freight routes are rural two-way, two-lane roads [14,15] with narrow widths, challenging alignment, few median barriers, and sub-highway speed limits of 70–80 km/h. It is unlikely that earlier findings about platooning feasibility are transferrable to such roads [12]. While automation may make vehicles and infrastructure more interdependent [16–18], the specifications for truck platooning are largely unknown, and it is unclear how roads authorities, which may have to regulate platoons and ready their infrastructure, should prepare [19]. This study explores platooning on Norwegian roads [20], which lend themselves well to the aforementioned description, with the added challenges of tunnels and mountain passes [12]. After a demonstration in 2018 [21], the Norwegian Public Roads Administration (NPRA) conducted a full-scale platooning field study in fall 2020, during which the data used in the present study were collected. The field study explored platooning system operation, driver interventions and road features. Collected data included videos, interviews, dialogue between participants, alongside fleet management and radar data. The following research questions are addressed:

1. How did the truck platoon perform and what challenges did rural road conditions pose?
2. In what conditions did drivers intervene with the platooning system?
3. Can technological and infrastructural solutions overcome the challenges?

Background

Platoons consist of one lead truck and one or more following trucks. For now, all trucks in a platoon are assumed accompanied by a driver. Radars, lidars and cameras enable Advanced Driver Assist Systems (ADAS) [22] to control the trucks longitudinally. The lead truck may also have a driver in charge of longitudinal control [23]. Hence, the following trucks would be at level 1 out of the five Society of Engineers (SAE) Levels of Driving Automation [24], and the leader could be at level 0 or 1. The Operational Design Domain (ODD) denotes the operating conditions for an Automated Driving System (ADS) [25], e.g., for the road, the vehicle, digital connectivity and weather. Steady-state platooning, i.e., no gear changes and acceleration [26], can yield 5–15% fuel savings [1,2,26] on flat highways at short headways, at 80-100 km/h speeds. Savings should improve as speed increases, since drag is a function of vehicle speed squared. Hence, platooning is less beneficial at low speeds [26]. As trucks are coasting or braking downhill, no fuel is used and no savings can occur. Beyond about 25-meter separations at 90-100 km/h speeds, fuel savings gradually diminish [27], and at 50-meter separations, the drag is similar to that of a singular vehicle, so no fuel savings will arise [26].

Some Norwegian policymakers are skeptical towards platooning, citing increased competitiveness of road freight versus sea and rail, negatively impacting transport policy objectives [28]. Others are positive, believing it will emerge in the 2030s and become widespread by the 2050s [29], citing improved safety and efficiency. If so, platoons may use existing roads, some of which have subpar features versus current requirements for road design, e.g., [30,31]. Others conclude that platooning requires freeway-like environments exclusively for automated vehicles [23], which would make implementation costly. Hence, real-world testing is needed.

Field-Trial

Building upon Finnish tests [32], a field study was undertaken to test platooning on Norwegian rural roads. Details of the study design are provided here. Driver workload and the use of low-cost radar sensors for estimating distances between the trucks are previous contributions from the field study [33,34].

Trucks and Adaptive Cruise Control

The three Scania semi-trailer trucks had 500 horsepower engines and automatic transmissions. The trucks and drivers are numbered 1, 2 and 3, based on their predominant positions in the platoon. Trucks 1 and 2 had equal mass (41 metric tons) whereas truck 3 was lighter (27.5 metric tons). All trucks had a prototype adaptive cruise control (ACC) system installed, enabling them to operate as a platoon when meeting certain criteria. While the modus operandi of the system under these criteria was supposedly different, the drivers did not perceive any differences. The system was based on radar and camera. The inter-vehicle distances used could not be shorter than those put forth in the Road Traffic Act [35], which prohibits tailgating. Distances were thus larger than in most literature, and resembled the set-up in [36]. With 2-3 second gaps at 80 km/h, for instance, the trucks drove 40–60 meters apart. Drivers activated the system using buttons on the steering wheel, and deactivated it by using the buttons, the brake pedal, or the retarder lever. The system was unaffected by gas pedal interaction. Steering wheel buttons were used to choose among five gap sizes, indicated by horizontal bars in the dashboard. Two bars were commonly used. The distance represented changed dynamically as a function of vehicle speed. The system became available when speed exceeded 15 km/h. Once active, the trucks would automatically adapt their speed to keep a safe distance to any preceding vehicle. A platoon connection, shown in the instrument cluster as a chain link, became available when the speed hit 60 km/h or more, while trailing behind a truck, and either of the two closest following distance settings were active. If the chain link was active and the speed dropped below 60 km/h, it remained so until the speed dropped below 40 km/h. When this happened, the system classified the platoon as disconnected and ACC automatically took over. If speed was reduced further, eventually dropping below 15 km/h, conventional ACC was automatically disconnected. A visual and audible warning signaled that longitudinal control was transferred back to the driver. If he wanted to activate it again, he would first have to manually accelerate the truck up to 15 km/h. The chain link required connection to the Scania cloud via cellular networks. The trucks had a Lane Keep Assist (LKA) system which provided limited lateral support. Nevertheless, drivers steered manually throughout.

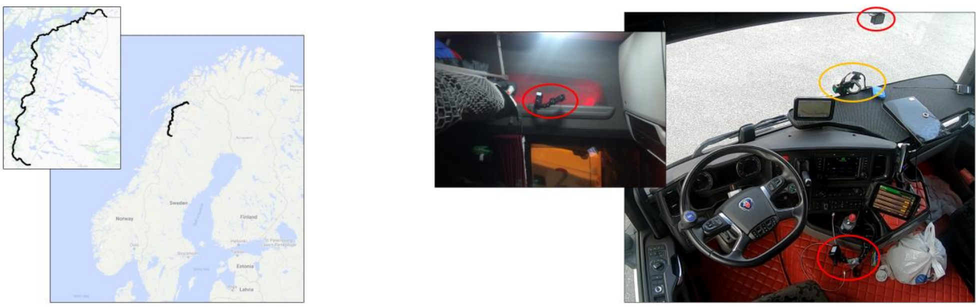
The vehicle could interfere with the platooning system through traction control (1), downhill speed control (2) and eco-roll (3). The truck would automatically disable the system in low-friction situations, until detecting sufficient friction again. In the meantime, the driver would need to perform longitudinal control manually. The downhill speed control (DSC) set the maximum speed for the system, and the truck would automatically brake if exceeded. To ensure that the platoon did not exceed the speed limit, DSC speed was mostly set just below the speed limit, and always higher than the ACC speed. The trucks also had an eco-roll system which engaged neutral in hilly terrain [37], allowing them to freely roll over crest curves. Using maps, the trucks knew the road geometry three kilometers ahead, and were supposed to choose optimal gears and speeds [38]. During non-platoon driving, this would cause acceleration as the truck enters upgrades, to limit speed loss, prior to disengaging the engine at the crest. It would also accumulate speed in downhills, within the bounds of the DSC. After breaks during the field trial, the two followers usually started with identical settings, and, to retain connection, these exceeded those for the lead truck. On the ACC/DSC, the followers mostly used 80/83 km/h, and 85/89 km/h, respectively. Truck 1 primarily used lower settings of 75/78 km/h. Driver 3 started changing the settings at his own volition underway, while driver 2 mostly kept them unchanged.

Method

Figure 1 (a) shows the 380-kilometer test route, driven over 7.5 hours, between two toll stations on the Norway-Sweden border. It was traversed in the northbound direction, mostly spanning European route 6, an important and commonly used freight route with average daily traffic of 1400, with 25% trucks [39]. National route 77 and European route 10 were also briefly used. The platoon encountered a mean of 2.8 oncoming trucks and 16.3 cars per 10 minutes, though most were encountered in groups near towns. Limited sections consisted of wide, modern two-way, two-lane road with 90 km/h speed limits (5% of the time). However, the route predominantly traversed a mountainous, coastal region, i.e., difficult with respect to horizontal and vertical curvature and the prevalence of narrow tunnels which do not meet current safety requirements [39,40]. Speed limits along the route were mostly 80 km/h (79% of the time). The tunnels on the stretch are narrower than permitted by current design handbooks [41], with a carriageway width of 5.5–5.7 meters and low overhead clearances (below 4.2 meters). For context, for opposing heavy vehicles to pass one another comfortably, a width of 8.5 meters or more is recommended [20]. In fact, truckers refer to these tunnels as "*mine shafts*" [42]. Other geometric requirements are also often exceeded [43], with steep inclines and declines, and difficult hairpin turns. Around 10% of the total stretch was comprised of horizontal curves with less than 250-meter radii, and 6% of its length had vertical gradients exceeding ±7%. Signs warning of adverse horizontal geometry, including narrow road widths, were encountered for a total of 115 times along the route. Three percent of driving time occurred on narrow rural stretches without centerlines. There were 11 and 5 signs warning of steep uphill and downhill gradients, respectively. The road occasionally passed through small, urbanized areas, with roundabouts, speed bumps and traffic, causing slowdowns for the platoon.

The route was deliberately chosen for the study as it would challenge the platoon. Traffic, road alignment and different engine-to-weight ratios [44] were expected to disrupt its stability, causing the gaps in the platoon to contract and expand, yielding high fuel consumption [45] and issues related to keeping set speeds. This was presumed to necessitate driver input, or communication between drivers, which was achieved using VHF radios. Participants conveyed important information, e.g., ACC settings, over radio. Excluding the drive from Finland through Sweden to participate in the field study, the three truck drivers did not have experience from driving together, but they had all previously driven in Norway and had used ACC before. While encouraged to use the platooning system, the drivers were told to resume longitudinal control when deemed necessary for safety. They were free to use Global Navigation Satellite System (GNSS) navigation [46] or other aids. Each truck had a passenger serving as conversation partner and observer. While difficult weather is prevalent in this area [40], conditions during the trial were good. The road was mostly dry and free of ice, sleet and snow, with ambient temperatures around 0 °C. Sleet and snow were briefly encountered (15 minutes) on a mountain pass at the end of the field study.

Data logged by the in-vehicle computer, e.g., on platoon system engagement and integrated sensor outputs, were not available. Third-party equipment was used instead, see Figure 1 (b), alongside output files from a fleet management system (FMS) provided by the carrier [47]. The set-up was identical in each truck, and included a radar sensor [34] which measured the distance to the preceding truck, and three action cameras [48] which filmed the driving scene and all interaction of the driver with the pedals and the steering wheel. The cameras also captured dialogue in the trucks and over radio. The term *preceding truck* is relative, and refers to the truck located in front of the truck in question. *Leading truck* or *leader* refers to the first truck, and *following trucks* or *followers* refer to both the middle truck and last truck together [34].



(a) **(b)**

Figure 1 (a). Test route. Both days shown. **(b).** Cameras (red) and radar sensor (orange) in each truck.

Data Analysis

The study sought to identify situations where the platooning system was disengaged, as such periods may represent the presence of barriers or challenges. Some disengagements were automatic, while some were initiated by drivers, and both of these types of disengagements are discussed herein. The following data were used to identify and assemble an understanding of these situations.

Interviews and Conversations Between Participants

The attitudes, expectations and experiences of the participants were collected qualitatively. Semi-structured interviews were conducted twice per driver; before the field study and midway through (15 and 30-minute durations, respectively). Moreover, participants freely conversed amongst themselves and over radio during the field study, and the researchers occasionally posed questions to elicit discussion. Qualitative data were transcribed, coded and organized into themes using NVivo 12 [49].

Video Observations

The Behavioral Observation Research Interactive Software (BORIS) was used to synchronize and code the videos [50], establishing a timeline of events [51] for exploring their surrounding contexts. Onwards, italics are used to refer to the video codes, see Figure 2. A dashboard camera provided footage of the driving scene, i.e., traffic and infrastructure. A cabin camera mounted on the door, over the head of the driver, filmed hand gestures, revealing interactions with the automated system through retarder use and adjustments of speed or distance settings. Lastly, a pedal bay camera filmed interventions with the platooning system through accelerator and brake pedal applications. Most driver behavior codes are similar to those defined in [52]. Videos were coded separately for each truck. Since they traveled together, at similar speeds, infrastructure events and durations should be near-identical for each truck. After coding, events lists were compared to eliminate coding errors. Platoon system engagement status, i.e., off, chain link active or inactive, could not be coded, as the symbol was difficult to discern in the instrument cluster. Segments during which one or several trucks suffered camera outages were removed for all trucks, ensuring consistency. Remaining videos lasted 6 hours (81% of total driving time). Pedal interventions, i.e., foot behaviors, often had multi-second durations and were thus coded in BORIS as state events, while hand behaviors were instantaneous, and were thus coded as point events.

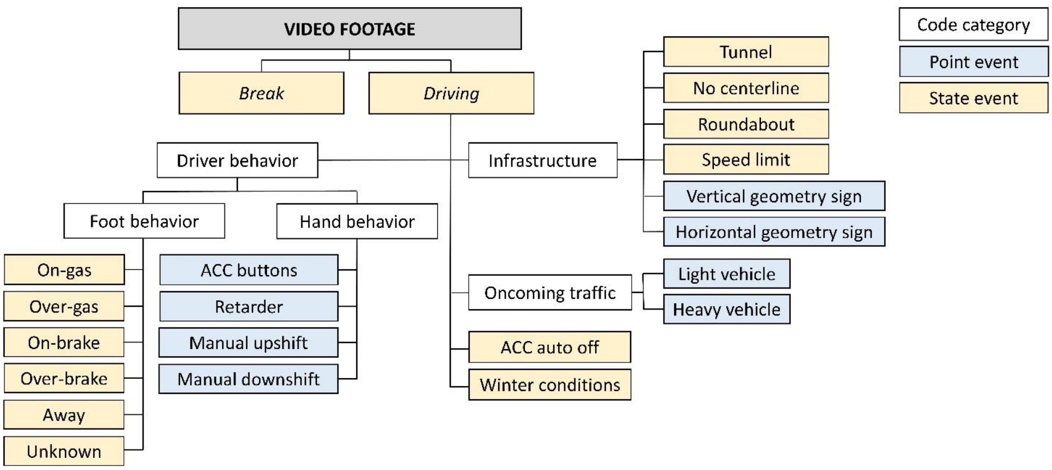


Figure 1: Overview of BORIS annotations.

Fleet Management System

The FMS logged speed [km/h], fuel level [%] and GNSS position at an average frequency of 0.02 Hz. While driving, it logged around 500 data points for each truck. 84–85% of loggings were made once per minute, 14–15% were made twice, and 0.5–2% were made three times per minute or more often. Hence, loggings were rather infrequent and did not always temporally coincide for the trucks. Nevertheless, FMS data can be used as an input for exploring the overarching operational performance of the platoon.

Results

This section explores the operational performance of the platoon, including speed, inter-vehicle distance and fuel use. It also presents findings relating to barriers or challenges to platooning from infrastructure and road conditions, and aims to identify and assemble an understanding of these situations. Those situations which warranted driver interventions are explored further.

Speed and Separation

The average speed of the platoon across the field study was 57 km/h, but this value was weighed down by frequent breaks. Hence, the mode, i.e., the most frequent speed value, provides a better overview of the speed during nominal, real-world operation. The mode speed was 62 km/h, i.e., significantly below the predominant 80 km/h speed limit, indicating the inherent difficulty of the route. The SINTEF Energy Module [53] provides a baseline average speed of 62 km/h for solitary trucks at 41 metric tons on the same stretch. Hence, platooning only briefly delayed the trucks, if at all. Speed was greater or equal to 80 km/h for only two percent of the time, due to strenuous uphills and conservative driving by the leader. The highest-speed measurements were recorded on higher-quality road segments, on which variability was lower than on slower-speed, lower-quality segments with features which necessitated speed changes. Even on favorable, flat and wide stretches with 90 km/h speed limits, the platoon mostly operated at speeds 77–79 km/h, i.e., below those used in previous studies, e.g., [10,54].

Speed consistency is key for platooning [55], and it is affected by road design [1] and interactions with other traffic, which cause variations in separation distances between the trucks. The correlation between speed and separation, and the variability of these factors over time, were explored in a comparison between a high- and low-standard road stretch, the specifics of which are provided in the Appendix. Higher speed and short, constant following distances seem to be beneficial for platoon operations, while lower speed and higher distance variability seemed to be disadvantageous. In fact, speed variability for the platoon was more than three times greater for the adverse stretch than for the favorable one (12.9 versus 3.3 km/h), suggesting that adverse road geometry impacts platooning by lowering speed consistency. Similarly, the distance variability during the adverse stretch was more than twice that for the favorable one (12.6 versus 5.7 km/h).

Fuel Consumption

In pre-trial interviews and through oral commentary, the drivers stated that they were familiar with the slipstreaming effect, and that they expected lower fuel use for the follower trucks. Over time, however, commentary revealed a realization that the route necessitated much higher fuel use than they expected. While the drivers cited adverse road geometry, truck mass, and the driving behavior of the leader as main culprits, one more factor should have been added, i.e., the large distances used. In fact, the platoon mostly operated at separation distances which were borderline sufficient to achieve savings [26], at 47–50 meters (std. dev 5.6–5.7 meters). The most strenuous mountain passes, which had 80 km/h speed limits and combinations of sharp horizontal curves and extreme gradients, cf. [33], provided even less favorable conditions. There, average separations were smaller, at 37–41 meters (std. dev. 11–14 meters), but speeds were also lower (56–59 km/h), reducing the fuel-saving potential of platooning. Moreover, as the trucks could not exceed their DSC speed, the kinetic energy owing to platooning in downhills were unrealized. Thus, compared to flat routes, hilly ones provide less time for which to save fuel via platooning. Fluctuating gaps on such roads also increase the number of instances of larger separation, where the slipstreaming effect diminishes [26]. During the trial, fuel use was reported orally in steep upgrades. Lacking a baseline, and due to the 40% lower mass of truck 3, only the fuel use of trucks 1 and 2 are comparable. These were often similar, ranging between 180–270 liters per 100 kilometers. Levels of remaining fuel (%) were reported among the FMS data, and trend lines for rate of fuel use per truck were established. In fact, truck 2 had slightly larger fuel use than truck 1 (0.7–4.4% higher). While no reference is available from the trial, a colleague of the authors which previously worked as a truck driver with experience from the same route, was asked for his opinion. He stated that the reported fuel use, when aggregated and translated into liters, conformed to his experiences from manual, conventional truck driving. Towards the end of the study, occupants in truck 3 noticed that the platooning system and eco driving functionalities seemed to conflict: On crest curves, the transmission would engage neutral, coasting to save fuel. This, however, caused its speed to decrease and the distance to truck 2 to increase, and the truck would accelerate downhill to reach the prescribed settings. Thus, platooning appears to have caused no fuel savings and perhaps also increased fuel use, since keeping preset distances to preceding trucks on roads with constantly changing vertical grades causes excessive acceleration and braking, as suggested by [56].

Driver behavior

Behaviors were largely consistent for the same drivers over time. Due to wanting to "(…) *have more control over how I roll downhill and slow down",* driver 1 drove manually, where the pedals and retarder were used to slow the platoon. He often alternated his right foot between the brake and accelerator, in addition to short *over-pedal* periods. His behaviors were rather reactionary, as opposed to proactive. Excluding the first 15 minutes of the field study, where all drivers drove manually, the two followers used the automated system almost exclusively for longitudinal control, with little other input. Driver 3 intervened the least, as shown in Figure 3. The drivers used the initial period to acclimatize to the road and obtain the correct distances between the trucks before activating the system. For both followers, most pedal interventions occurred in transition periods as the platoon entered or left the road. These interventions are not as interesting as those that occur during on-road driving. The second-most frequent situations where interventions occurred, involved the platoon having to slow down considerably, due to e.g., intersections or slow-moving traffic.

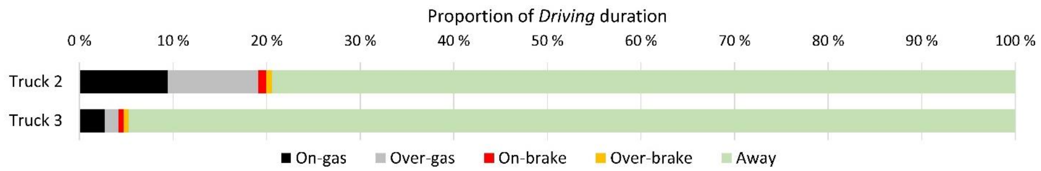


Figure 3: Proportions of driving duration for foot behaviors for the two followers.

The types of hand interactions differed between followers, presumably due to personal preferences. They did, however, have similar total numbers. As shown in Figure 4, driver 2 shifted gears manually more often than driver 3, who instead tended to adjust ACC settings. Truck 3 retarder use stems nearly exclusively from the 15-minute period of manual driving at the start of the study. For both followers, manual shifting occurred in upgrades, and when accelerating from standstill after breaks, but before having activated the ACC system. Combining actual interventions shows that, on average, trucks 2 and 3 had 1.1 and 0.5 interventions per minute, respectively. In contrast, truck 1 had 3.7, and he used the retarder more than 800 times.

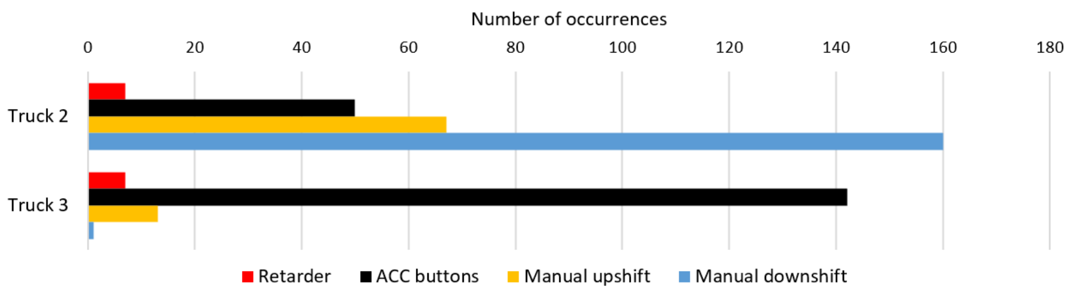


Figure 4: Number of hand behaviors for the two followers.

Vertical Gradients

As also reported in [10,26], correct and coordinated timing of gear shifts on steep ascents was found to be key for retaining platoon connection and for keeping a fuel-efficient speed profile. The trucks struggled maintaining speeds on steep grades, frequently dropping below 40 km/h during strenuous climbs. Driver 1 often downshifted manually to retain speed uphill, while the followers mostly relied on their automatic transmissions to do so. Hence, the first truck executed more strategically timed gear shifts than the following trucks did, frequently causing them to lag behind, before their platooning systems sped up again to close the gap which had appeared. On one climb, in particular, the gear chosen by truck 3 was so erroneous that the situation had to be resolved through two successive downshifts to keep the truck from stalling, causing sharp deceleration while trucks 1 and 2 drove off. Wanting to see how the situation unfolded, driver 3 did not intervene. In general, interventions in uphills were rare, and occurred mostly on very steep sections. In his pre-trial interview, driver 2 stated that he believed that he would disconnect the system in uphills, but he did not end up doing so. Occasionally, however, he accelerated manually uphill. Truck 3 never did so, and the combination of manual acceleration and better-timed gear shifts for the two preceding trucks occasionally made it fall far behind. For truck 2, manual shifts were predominantly downshifts, and they seemed to occur mostly for reducing speed in downhills.

When driver 1 realized that the followers were lagging behind, he occasionally asked over radio whether they were connected and satisfied with the current speed, adjusting his speed slightly based on their responses. However, differences in personal driving styles materialized between the drivers, particularly on downgrades. While driver 1 was aware that "*(…) we save more fuel if we drive closer*," he was concerned and careful, preferring the followers use the maximum distance settings on grades, in case he suddenly had to brake. He perceived uphills as less critical, citing lower speeds and more time for the followers to intervene to avoid rear-end crashes. Even so, the others preferred having more consistent gaps, citing two-second headways as comfortable and ideal on dry roads. When driver 1 would suddenly brake in downgrades, driver 2, observing the brake lights, often readied his foot to intervene, but he seldomly did so. Driver 1 was mostly criticized for driving too fast downhill before engaging the brake. As the trucks would successively brake, harshness would propagate rearwards in the platoon, frequently causing discomfort in truck 3 on downhills, in sag curves and before horizontal curves. Hence, driver 3 cited a wish for earlier, more proactive and consistent speed reductions. Much of the instability was likely caused by truck 3 being lighter. All participants reported that "*The last car [experiences] a yo-yo-effect that is not nice at all*." Videos from overhead cameras reveal that the term was frequently used alongside hand motions, describing oscillations in separation and irregular behavior for truck 3 when traversing crests and descents: *"When we go uphill, the last one that is lightest cannot get faster. But when we get over, the heavy ones are starting to go downhill, and the lighter one (…) has difficulties to [reach].*" Driver 3 stated that the driving would have been smoother if the trucks were equally heavy: "*I am sure that, if all the trucks had the same weight, (…), they would react the same way*." Eventually he started adjusting ACC-DSC settings: "*The lightest truck in the convoy has to do more work than the trucks that have the same weight, (…). If I play with the speed, all the time, I can make it smoother*." Hence, the frequent ACC adjustments by driver 3 were strategic, countering the weight differences between truck 3 and the two others, which, if left unattended, were likely to exacerbate the yo-yo effect.

Winter conditions were occasionally discussed in light of the yo-yo effect, suggesting that the trucks could automatically regulate safe limits for distance and braking on slippery and sleety roads. During the short period where such conditions materialized, see Figure 5, driver 1 disengaged the ACC system and drove manually until the study ended: "*When I brake, the second car comes from behind and the third car brakes even harder (…). There are risks [of rear-end collision] when it is slippery. In these conditions it's no point to drive [platooning]*." Driver 3 did not intervene in winter conditions, and in only instance, when traversing a curve during a decline, did he preemptively hover over the pedals (*over-gas and over-brake*, see Figure 2). While only driver 2 resumed manual longitudinal control, both followers expressed skepticism towards using the system in such conditions.

(a) (b)

Figure 5. Sleety winter conditions. Upgrade seen from escort car (a) and truck 3 (b).

Horizontal Curvature

The platoon traversed horizontal curves of varying radii at different speeds and separations, see Figure 6. While being rather rare, the curves with the sharpest radii (approx. 80–120 meters), and hairpin turns (below 80 meter radii) in particular, were the most adverse. If curves were moderately sharp, the platoon connection was often broken and regained repeatedly as the trucks negotiated the curve, since the system was occasionally unable to determine the type of vehicle preceding it. However, ACC still detected the preceding vehicle, so this had no consequence to the drivers. In sharper curves, however, the followers routinely experienced the preceding truck leaving the field-of-view of the ADAS sensors for a few seconds, causing intense acceleration. No longer detecting a vehicle before it, the truck assumed a clear path, accelerating to comply with predefined settings which were often higher than the current speed. When the system regained visibility to the preceding truck, it was now located much closer than the prescribed gap size, causing automatic harsh braking: "*If the back of trailer goes away, then [the ACC system] sees that the distance is too big and starts to accelerate. We were on the curve, then the trailer was gone, and it started speeding*." At the start, this came as a surprise to the drivers. In subsequent curves, the followers would tend to preemptively approach or press the brake pedal, or disengage the system in anticipation. They also experimented with slightly cutting sharp corners, increasing the likelihood of remaining connected. The sharpest curve, a hairpin with a 16-meter radius, had two followers react differently. Driver 2 started hovering his foot over the pedals when halfway through. He did not intervene, reverting to resting his foot far away immediately afterwards. Driver 3 deactivated the system using the buttons as he entered the curve, driving manually before reengaging it and withdrawing his foot when the curve was traversed. Generally, driver 2 was likely to intervene if the road alignment only provided limited sight distances.

Horizontal curves following steep downhills frequently warranted the following drivers to prepare to intervene (*over-brake*). In such situations, interventions (*on-brake*) were most frequent when the followers were quickly approaching the preceding truck, and involved quite long periods of braking. Over time, driver 1 realized that maneuvering the sharpest curves slower than strictly necessarily made the followers more likely to retain connection, as inter-vehicle distances are shorter at low speeds, and his trucks is thus less likely to stray away from the field-of-view of the middle truck. Based on previous experiences, the drivers stated that platooning was more difficult in Norway, due to the high frequency of tight curves: "*In Helsinki, the up and down is straight, it's not curving. This is totally different. Because [there, you never] lose the trailer in front of you*." Hence, rural roads with rolling hills and tight turns proved difficult for the platooning system.

(a) (b)

Figure 6. (a). 16-meter radius hairpin in steep 6.2% uphill **(b).** 80-meter left-turn in a slight downhill. Both views seen from truck 3.

Tunnels and Narrow Sections

The platoon traversed 23 tunnels (6% of total driving time, i.e., 28.5 min). The longest was 4.5 kilometers, and the average length was 1.1 kilometers. In sum, tunnels accounted for 30 kilometers, or 8% of the field study distance. While some tunnels were curved, the sharpest having a radius of 250 meters over its 800-meter length, most were straight. A few tunnels were quite steep, at 4–5% inclines and declines. Driving speeds within tunnels were generally lower than during open-road driving, though FMS speed values do not reflect this, as no loggings occurred in tunnels due to the lack of GNSS connectivity. Four tunnels were traversed which did not have centerlines, or only had them for parts of the tunnel (1.5 minutes of driving time). While this is the case also for solitary trucks, difficult situations arose when the platoon encountered oncoming trucks in narrow tunnels with low overhead clearances, see Figure 7. Both the oncoming and the lead truck would slow down to ensure safe passage. Hence, speeds for the platoon were reduced, often significantly, and the trucks frequently had to have their outer wheels on the outside of the edge marking to leave enough room for the opposing truck. Simultaneously, the drivers had to make sure that their cab or trailers did not touch the curving tunnel roof. In such situations, the followers usually had their foot over the pedals, ready to intervene. Such situations occasionally made the platoon speed drop below the 15 km/h ACC disengagement threshold, warranting interventions. This occurred both in tunnels with and without centerline markings.

As speeds were lower in tunnels, the separation distances were also smaller. The two following drivers commented that this adversely impacted their situational awareness: "*It was uncomfortable. When we get too close to each other, I cannot really get the whole picture of the tunnel*. (…). *I cannot see who is coming* towards us." From the drivers' perspective, and excluding the aforementioned disengagements owing to oncoming trucks, the behavior of the automated driving system was unaffected by tunnels. However, the platooning system operated through cellular connection to a cloud service, which was unavailable inside tunnels. "*In the tunnel, we are disconnected from the Scania cloud. So, (…) [the truck] uses still ACC with the same protocol*". The drivers felt no changes to the driving behavior at the transitions between areas with and without network coverage.

(a)

(b)

Figure 7. (a). Tight passage when encountering oncoming truck. **(b).** Narrow tunnel without centerline**.** Both seen from truck 3.

Road widths were mostly discussed when passing through tunnels. Even before encountering the tunnels, however, all three drivers ended up disabling their LKA systems. The LKA would warn drivers that they were approaching or slightly exceeding the road markings when negotiating curves. They conjectured that this was due to the roads being narrow, see Figures 7 and 8, and that LKA was more appropriate for highway use. Drivers 1 and 2, who had the least amount of local experience, were uncomfortable negotiating the first long and narrow tunnels on the stretch. The lack of shoulders inside tunnels was also an issue. A narrow railway underpass, see Figure 8 (b), also elicited feedback. Having no centerline, it was also located in conjunction with a fairly sharp 140-meter radius curve. Driver 2 had his foot over the brake, ready to intervene when passing through, but ended up not doing so. Driver 3, who had the most experience from Norwegian road conditions, was seemingly unaffected by it, and was also less affected by sharp curves and narrow tunnels in general. Driver 2 frequently alternated between hovering over and keeping his foot close to the pedals when approaching and traversing narrow tunnels, especially in situations with opposing trucks or no centerlines. Platoon speeds would often be moderate in these scenarios, as driver 1 would have reduced his speed.

(a) (b)

Figure 8. (a). Narrow rural road **(b).** Narrow railway underpass in curve with limited sight distance. Both seen from truck 3.

Intersections and Urbanized Areas

The platoon traversed five small, urbanized areas. Roundabouts were the main intersection type, and 11 were traversed. Straight movements through roundabouts tended to work fairly well. Speeds usually exceeded the 15 km/h lower threshold, so the ACC system mostly remained active. Particularly when going straight when there were no other vehicles present, the followers tended to have the system engaged, though generally keeping their feet closer to the pedals than during open-road driving. Some maneuvers, however, were so sharp that there were occasions without sensor connection. In the tightest roundabouts, where field-of-view was most likely to be lost, the followers would preemptively disengage the system and traverse them manually. As driver 2 stated when interviewed: "*When we drive in roundabouts and the first car starts to turn, I can't make contact with the car in front. My car started [accelerating]*." While acknowledging that "*this automatic system is maybe not designed for roundabouts, it's mainly for the highway*", driver 3 started adjusting the set speed to 20 km/h when traversing them, so disconnections did not cause harsh acceleration.

Two three-way intersections were encountered. The first was driven without interventions by either follower (driver 3 was *over-brake* but did not intervene), while both followers deactivated the system when approaching and traversing the second one. The former intersection was situated on a completely flat area, while the latter was located at the base of a steep uphill mountain pass. One of the urbanized areas had the platoon slowly traverse speed bumps. As the speed fell below the 15 km/h disengagement threshold for the automated system, the two followers drove manually for a few minutes until having passed through the city center and back onto rural roads.

Concluding Remarks

This section discusses the experiences from the field trial in light of potential technological and infrastructural solutions, and aims to provide pointers to roads authorities and academia for future initiatives.

The field trial showed that the truck platooning system was feasible on high-speed rural roads with forgiving alignment. There, the platoon remained connected, driving in a coordinated manner with consistent speeds and separation distances, but this was mostly expected. Roads with subpar geometry, on the other hand, were more difficult. While the trucks mostly remained connected also on such roads, sharp curves, narrow tunnels and alternating inclinations caused the platoon to contract and expand as the trucks successively traversed different road features. On average, the trucks maintained quite low driving speeds. In sum, the roads lent themselves poorly to obtaining fuel savings from platooning. Nevertheless, the route is known to be adverse also for solitary, manually driven trucks, and fuel use during platooning should be properly tested against such a baseline. Driver profile, including the eco-driving experience of the driver, will greatly impact any manually driven baseline, potentially yielding fuel savings exceeding 5% [57]. Hence, the same drivers should be involved in the baseline run as in the platooning run, and both should ideally be repeated multiple times. In the field study, stretches with rolling hills and sharp curves saw a yo-yo effect whereby the trucks performed gear shifts uncoordinated, causing sharp acceleration when falling behind, and harsh braking when getting too close to the preceding truck. The hypothesis of driver 3, whereby platooning in rural conditions offsets fuel savings from eco-driving, should also be tested. Drivers were highly skeptical towards using the platooning system on slippery roads, citing risks of rear-end collisions.

The observed challenges are partly attributed to the open, and also highly realistic, test framework of the field study. Since the drivers did not use the closest gap setting, it is unclear whether this would have resulted in smoother driving. It is also unclear whether the system behaved any differently than what a conventional ACC system would on the same stretch. The issue of lost connection in curves presumably also depended on the prescribed ACC gaps. The longer distance settings would better accommodate acceleration following connection losses, while acceleration at short following distance would result in dangerous situations with the potential for rear-end collisions. However, connection losses would likely be less frequent at short distances. This trade-off should be investigated. Drivers also wished the system reacted faster when the preceding truck changed its speed. One participant suggested that Vehicle-to-Vehicle (V2V) communication would have resulted in smoother operation, due to its ability to instantaneously transmit driving commands [2] between the vehicles: "*Control signals and changes would have been utilized straight away, [as opposed to by being detected through] the changes in vehicle behavior in front*." The trucks did have capabilities for V2V communication, but it was not used. Doing so would have required obtaining a test permit from the Norwegian Communications Authority (NKOM). For future testing, such a permit should be obtained beforehand, and initial conversations with NKOM reveals that such a permit should be fairly straightforward to obtain, especially for testing in rural areas. Perhaps foreshadowing the usefulness of V2V communication, the drivers suggested having an active phone conversation continuously during the drive, relaying relevant information, and this becomes increasingly relevant if following distances are reduced. Cooperative Adaptive Cruise Control (CACC), e.g., [55] could also be used to identify safe separation distances, and coordinate gear changes, truck weights and speed profiles when determining appropriate gaps. An exemption from the Road Traffic Act [58] could also be obtained for testing purposes, allowing for smaller following distances.

If roads authorities are tasked with certifying roads for platooning operations, 80 km/h speed limits seem to be poor indicators for the ability of Norwegian roads to accommodate platoons. This is perhaps unsurprising, as this is the general threshold speed limit outside urban areas [59]. Platooning using the technological set-up herein would be better suited for high-quality rural roads, e.g., two- and three-lane expressways at 90 km/h, and also for low-traffic, high-standard undivided two-lane roads with forgiving horizontal and vertical geometries. While many of the issues faced by the platoon can be solved by infrastructure adaptations, technology developments, or combinations thereof, the latter is presumably more realistic from a cost-benefit standpoint. The drivers also recognized this, as "(…) *you cannot change the roads as quickly as [the] vehicles*." They suggested that the loss of connection in sharp curves could be solved using sensors with wider fields-of-view, or sensors which move along with the steering curvature, and suggested connection losses to be warned audibly, so drivers would not be startled by the subsequent bursts of sharp acceleration. However, physical infrastructure improvements are still key to eliminate the worst bottlenecks. As the drivers started adapting the ACC-DSC settings to counteract yo-yo effects, it is unclear which of the observed effects stem from deficiencies in technology, infrastructure or the drivers. Hence, future field studies should have drivers change ACC-DSC settings only at designated times or locations, and they should otherwise be discouraged to intervene, unless for safety.

In the real world, the number of available trucks to partake in platoons on rural roads may be somewhat scarce, requiring coordination and waiting to link up [33]. Trucks in the real world will likely also have different engine-to-weight ratios, which may exacerbates the challenges. Larger engines may help counteract yo-yo effects, and future electrification of the trucking fleet will presumably also be beneficial, by improving torque and removing the destabilizing effects of gear changes. Nevertheless, road freight in rural areas may be better served by highly automated, i.e., driverless, single trucks. As stated by one of the participants: "*In the big picture, the fuel saving [are] not the point here*", conveying his belief that the benefits from platooning will chiefly accrue from the operation of driverless following trucks. However, this introduces constraints on infrastructure readiness which are not yet understood. Lateral automation has only briefly been discussed herein, through the faults of the LKA system in being useful for the drivers on the winding roads. This suggests that safe lateral automation will be challenging to accomplish, as error margins are small. It is also unclear how platoons would operate in tunnels, having limited GNSS and cellular connectivity. The same goes for speed bumps, intersections, roundabouts and sharp curves, neither of which are ideal for platooning operations. Hence, the operational readiness of semi-automated truck platoons on Norwegian rural roads is questionable, and more testing and development is needed.

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Appendix

Data from NVDB [60] were used to extract road geometry from roughly the best (1) and worst (2) stretches encountered, illustrating its correlation with speeds and separation distances. Vertical gradients and horizontal curvature were extracted, visualized and binned, to calculate the proportion of roadway lengths in each bin. Curves with radii above 2500 m were considered straight, and no distinction was made between left and right curves. Straights were removed, magnifying the shorter-radii bins. For the same reason, flat segments (i.e., with gradients ± 2%) are also not shown. Negative gradients are downhills in the direction driven during the field trial.

Stretch 1 is a wide, modern and flat high-quality road with gentle curves, traversing the floor of a valley at 90 km/h speed limit. Stretch 2 traverses a mountain pass, with combinations of sharp horizontal curves and extreme gradients, cf. [33], at an 80 km/h speed limit. Their geometries are shown in Figure A1. The same drivers served as followers and leader when traversing both stretches, and driving durations were similar. Stretch 1 was 52% longer, at 38 kilometers, versus 25 for stretch 2. Conditions were ideal in both cases, but there was less ambient light when traversing stretch 2. Except for a preceding car slowing down to exit the road at 10-11 minutes into stretch 1, there was no influence of external traffic, so the stretches are fairly comparable. Flat segments comprised 93% of stretch 1, but only 43% of stretch 2, so stretch 2 is much steeper. Almost 10% of stretch 2 were uphills at 7% gradients or steeper, and 7% was comprised of downhills (corresponding values for stretch 1 were 1 and 0%). Thus, stretch 2 was significantly more strenuous than previous field trials, e.g., [10] where 4% was the steepest. Stretch 1 has no sub-200 m radii horizontal curves, but 9% of stretch 2 was made up of such curves. Six curves on stretch 2 had radii below 100 meters.

Figure A2 shows speed profiles for the trucks, and Table A1 contains the associated statistics. Blue and brown shading denote stretches 1 and 2, respectively. Speeds on stretch 2 were lower and the variability was greater, both between each truck and for the same truck over time. Average speeds would appear to show consistent driving, but this was not the case. In fact, speed variability was more than three times greater for stretch 2 than for stretch 1, suggesting that adverse road geometry impacts platooning by lowering speed consistency. Periods at 90 km/h speed limit were most consistent. Stretches with 80 km/h speed limits, although only slightly lower, provide significantly worse conditions for platooning.

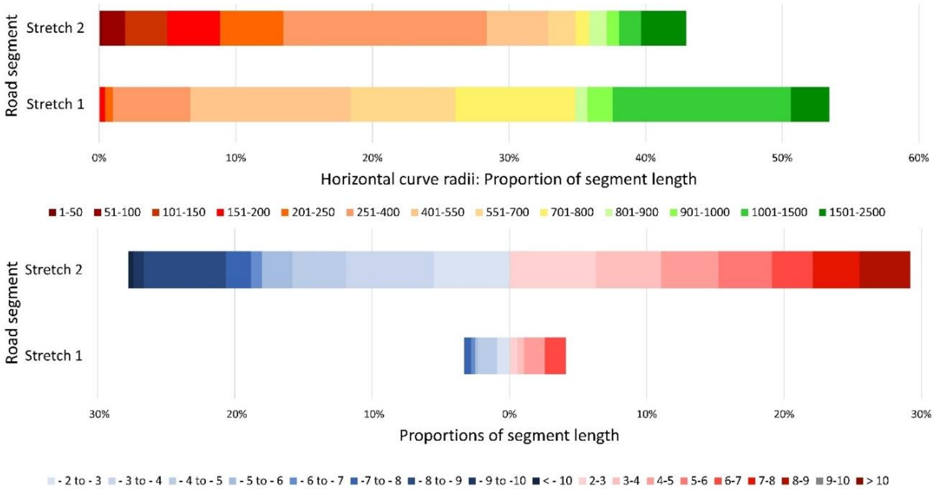

Figure A1: Proportion of horizontal curve radii (top) and vertical gradients (bottom) for the two stretches.

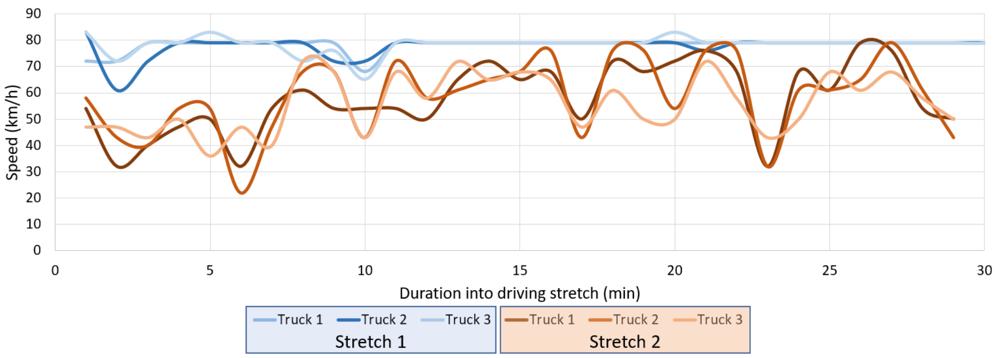

Figure A2: Platoon speeds for sections 1 and 2.

Table A1: Speed metrics (km/h) for each truck over the two stretches

Stretch	Speed metric	Truck 1	Truck 2	Truck 3
1	Average	78.2	77.8	78.5
	Standard deviation	2.5	3.8	3.4
2	Average	57.9	58.6	56.0
	Standard deviation	13.2	14.4	10.8

*Differing average speeds for the trucks were caused by infrequent loggings and measurement uncertainty.

In addition to the speed fluctuations shown in Figure A2, the adverse geometry of stretch 2 caused variations in inter-vehicle distances, i.e., making it harder to keep the platoon collected. Figure A3 shows the distance to the preceding truck, with shading as in Figure A2. Table A2 shows related statistics. Notably, the gap stays consistent for most of stretch 1, but not for stretch 2. For both followers, the distance variability during stretch 2 is more than twice that for stretch 1. At stretch 2, average separations were smaller, but speeds were also lower (see Table A1), lowering the fuel-saving potential. Moreover, as the trucks could not exceed their DSC speed, the kinetic energy owing to platooning in downhills were unrealized. Thus, compared to flat routes, hilly ones provide less time for which to save fuel via platooning. Fluctuating gaps on such roads also increase the number of instances of larger separation, where the slipstreaming effect diminishes [26].

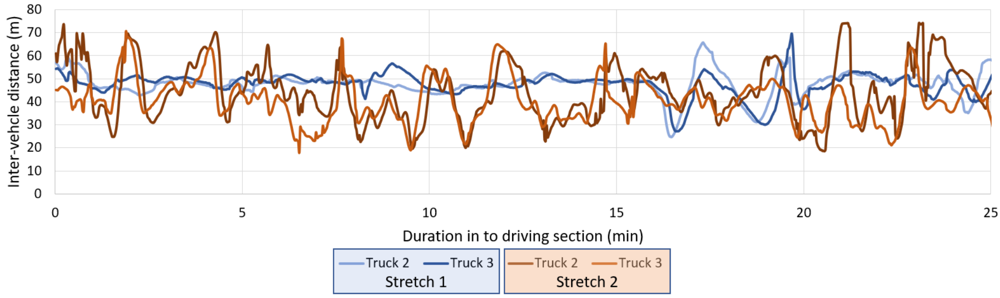

Figure A3: Inter-vehicle distance measurements (1 Hz) from the following trucks during the two excerpts.

Table A2: Metrics for inter-vehicle distances (m) between the trucks over the two stretches.

Stretch	Distance metric	Truck 1 to Truck 2 (m)	Truck 2 to Truck 3 (m)
1	Average	47.6	47.1
	Median	48.4	48.5
	Standard deviation	5.7	5.6
2	Average	40.5	37.3
	Median	37.6	39.7
	Standard deviation	14.1	11.0

Paper 4

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Lessons Learned From Industrial Applications of Automated Trucks for Deployment on Public Roads

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Abstract
Automated trucks may streamline road freight. While manufacturers and technology developers have long predicted their advent, technical and regulatory challenges persist, and systems beyond SAE level 2 are rare. However, systems at levels 3 and 4 are being adopted on industrial areas. Roads authorities want to study such applications to gain insights into requirements for implementing automated trucks on public roads. Two cases were studied here: Automated stone haulage, and automated snow removal. Interviews with project managers were used to identify opportunities and barriers, and evaluate the applicability of different technical, infrastructural and organizational solutions. The paper showcases the strengths and vulnerabilities of the two different solutions, and reflects on how they may be overcome for automated trucks on public roads. Road and winter maintenance are explored, alongside requirements for pre-mapping, localization and communication for each solution. Considerations on control and oversight, and on automation as an enabler for electrification are explored, alongside the importance of change management procedures.

Keywords: Automated trucks (1); Industrial automation (2); Heavy-vehicle automation (3); public roads (4); sensing (5); winter conditions (6).

1. Introduction
Automation of trucks on public roads may provide benefits for commercial actors, road users and for society as a whole, improving traffic safety and efficiency while lowering costs and emissions [1–3]. In particular, automated trucks allow for higher asset utilization while counteracting driver scarcity, cost pressure and low margins [4]. The extent of benefits unlocked depend both on the capabilities of automated trucks, and on the ability of the road network to support them. This is especially the case for trucks, as opposed to passenger cars, as they travel long distances and are heavily utilized [5]. Deployment of automated trucks may also be rapid, as carriers are incentivized by potential cost savings [2]. The self-driving industry has for many years foreshadowed the impending advent of autonomy [6]. Still, Advanced Driver Assistance Systems (ADAS) exceeding level 2, as defined by the Society of Automotive Engineers (SAE) Driving Automation Levels [7], are

mostly absent on public roads [2]. Examples of level 2 systems are Adaptive Cruise Control (ACC) and Lane Keep Assist (LKA). Current vehicle technology does not support automation at levels 3 and 4 on public roads. Enclosed areas provide higher feasibility [2], and personnel involved in industrial automation projects may have useful knowledge for deployment of automated trucks on public roads.

Industrial use-cases of automated trucks benefit from closed, strictly regulated areas. They are thus less complex than public roads. Nevertheless, there are many parallels, and such use-cases may provide insights into requirements for driving automation in a more general sense [2]. Using two case-studies of automated trucks on closed areas, this paper identifies technological, infrastructural and organizational factors which could serve as barriers or enablers for automated trucking on public roads. The research question reads: *What lessons can be learned from industrial use-cases of automated trucks to facilitate on-road deployment?*

2. Background

Many countries have adopted legislation for automated vehicle testing, e.g., [8], and public institutions are increasingly becoming involved [6], further facilitating their introduction [9]. The Norwegian Public Roads Administration (NPRA), which partly governs the design, operations and maintenance of the physical and digital road infrastructure in Norway, is trialing Automated Driving Systems (ADS), e.g., [10–12] and takes part in the ongoing MODI project, which aims to demonstrate SAE level 4 automated trucking at industrial sites and on public motorways in Northern Europe within 2026 [13]. The Norwegian road network mostly consists of rural two-way, two-lane roads, parts of which are narrow and have difficult alignment [14]. Due to topography, scarce population and low traffic volumes, motorways make up less than 1% of the road network [15]. Norway also has approximately 1.300 road tunnels [16], causing problems for vehicle positioning using Global Navigation Satellite Systems (GNSS) [17,18]. Adverse weather and winter conditions also cause problems for ADSs [3,19]. Norway provides opportunities to test how ADSs perform under demanding conditions.

An ADS operates under given conditions, i.e., its Operational Design Domain (ODD) [20], and simplifying the conditions may make up for shortcomings in functionality. Examples are full or partial removal of road users, operating on homogenous routes, and only during clement weather. Conceptually, small changes could be made over the entire road network, facilitating lower-level automated driving, i.e., still requiring human supervision and input. Alternatively, smaller areas may be fully overhauled, facilitating high-level, driverless automation [21]. Initial coverage may be limited, but it can scale over time [2]. While a spectrum of concepts exist for automated trucking on public roads, e.g., [22], most developments involve hub-to-hub highway driving [23–27]. Still, this is a challenging undertaking [28]. Automation may require more consistent maintenance [29] and new infrastructure components, for instance beacons for accurate positioning in tunnels [30]. Such equipment may help, e.g., [3,31], but may also induce maintenance demands. Digital infrastructure, such as maps, may also be required [32], and policymakers acknowledge this [33]. Automated vehicles may warrant changes to road design, e.g., speed limits, lane widths, curve radii, and other parameters [3,34], but it is currently unclear what makes a road “AV-ready” [6]. Two industrial use-cases of automated trucks were studied to uncover learnings to facilitate automated trucking on public roads.

3. Methodology

Digital, individual semi-structured interviews were conducted in the fall of 2022 with project managers for two different use-cases: Automated rock transport at the Brønnøy Kalk limestone mine (1), and automated snow removal at Oslo international airport (2). The latter location is hereby referred to as OSL, based on its International Air Transport Association (IATA) airport code. At the time, both projects were located at the border between research and commercial application. A general interview guide was adapted for each use-case based on publicly available information, e.g., [35–37] for Brønnøy Kalk and [38–41] for OSL. Open-ended questions allowed the participants to share their views and insights freely [42]. Questions comprised eight topics: Operation (1), infrastructure (2), vehicles and technology (3), weather-, driving-, and light conditions (4), organization and safety (5), government and regulation (6), business case (7) and project execution (8). Using the same general interview guide facilitated comparisons between the use-cases. At times, participants were asked to evaluate whether different parts of their use-case would be relevant for application on public roads. Hence, the interviews assimilated useful information for reflection. Each participant was interviewed for three hours, and the conversations were transcribed and reviewed.

On behalf of the OSL use-case, a senior representative from Avinor, the airport operator and project owner, was interviewed. He was trained as a machine operator, had worked at OSL his entire career, also on technical implementation projects and had received management training. The interviewee at the mining use-case worked for the hardware and technology supplier, Volvo Autonomous Solutions (VAS). VAS had a strong partnership with Brønnøy Kalk, who proposed the VAS representative to partake in this study on their behalf. He was a mechatronics engineer and had been involved with the project for 1.5 years. The two interviewees provided similar levels of technical detail, and both have approved the final version of this publication.

The two use-cases, shown in Figures 1 and 2, are similar in terms of scale and complexity. They also complement each other in capturing both central and rural geographic locations, and in the interface between technology and human supervision, thus having slightly different automation levels. The use-case at OSL operates only in winter, whilst Brønnøy Kalk operates year-round. Hence, both face adverse winter conditions, e.g., snow, ice, fog and frost, but Brønnøy Kalk faces surroundings which are more dynamically variable. In addition, Brønnøy Kalk handles difficult infrastructure, e.g., tunnels and curves. Both use heavy-duty diesel trucks. The OSL use-case bears resemblance to platooning, a term which refers to the concept of wirelessly linking trucks to save fuel and streamline road freight [43], potentially allowing for unmanned operation in the future [1]. At Brønnøy Kalk, the trucks operate separately, i.e., as free agents [5]. In comparison, the OSL approach may be more secure, due to the on-site presence of a human in the lead truck [4] for oversight and fallback. Projections for truck platooning made in the late 2010s have mostly failed to materialize [44,45], despite recent tests, e.g., [11,12,46]. While the OSL trucks drive too slowly to save fuel, the use-case may still be informative. Brønnøy Kalk is the first application of its kind in Norway using fully driverless trucks without safety drivers [47]. Automation of separate trucks might be the preferred solution to road freight in areas where truck volumes are too low to justify the formation of truck platoons [1].

4. Overview and Comparison

4.1 Operations and Infrastructure

Avinor is automating snow removal on runways at OSL. Six identical, modified trucks operate simultaneously in a staggered platoon formation at 25-meter gaps. Each truck is 28 meters long, significantly longer than semi-trailers, and hence not intended for use on public roads. Once fully operational, only the lead truck will be manned, by an Automated Snow Removal (ASR) operator, while the followers are unmanned. All of the trucks are self-driving, so the ASR operator does not normally interfere with the pedals or steering wheel. Using pre-planned digital routes, a fleet controller administers the platoon, communicating between all trucks through the cellular network. The trucks use GNSS for localization, and have no local sensors for object detection. The ASR operator communicates over radio with a snow clearing manager located in an external vehicle, who communicates with the watch commander in the Air Traffic Control (ATC) tower. ATC administers all runway activities. ATC can view the platoon location digitally. The trucks stop automatically if positioning or communications malfunction. Using a separate communications system, emergency stop buttons are located in the tower, in truck cabins and around their exteriors. The operation stops promptly if such a button is pressed. YetiMove and Øveraasen are technology and hardware suppliers [38].

Figure 1: Automated Snow Removal (ASR) at OSL **[48]**.

Brønnøy Kalk partnered with Volvo Autonomous Solutions (VAS) for automating rock haulage from a quarry to a crusher. The site at Brønnøy Kalk is more complex than the wide, flat and open areas at OSL. The two locations at the mine are connected by five kilometers of mostly paved roads, traversed almost exclusively in narrow tunnels, mostly 7 meters wide. One tunnel is long (3.5 kilometers) and has steep grades (8.8%), while the other is short and flat (0.8 kilometers). Both are illuminated and ventilated. Some horizontal curves are sharp (20-meter radii). Road sections are classified either as single or meeting lanes, based on whether opposing trucks can pass. Previously, drivers would signal with headlights and communicate over radio to avoid meeting in narrow areas. Once fully scaled, seven trucks will traffic the site. At the quarry, a human operator loads each truck with stone using a wheel loader, i.e., a powerful construction machine with a bucket [49], before dispatching them using a tablet. The crusher site is overseen by the crusher operator. In this specific solution, the route has been pre-mapped, and lidars are used for navigation throughout, except for in the quarry, where it is also GNSS-based. Rock walls at the roadsides mostly provide sufficient texture for navigation, but areas that did not, are instrumented with wooden lidar reflector walls. The area to which the trucks are constrained, termed the Autonomous Operation Zone (AOZ), has full cellular coverage. Emergency stop buttons are located along the route, and portable ones are worn if employees enter the AOZ. VAS currently runs the operation, but once scaled, Brønnøy Kalk will oversee the trucks themselves, purchasing ton-kilometers using a transport-as-a-service model.

Figure 2: Automated haulage of limestone at Brønnøy Kalk **[35]**. **Left:** Tunnel entry after sharp left-curve. **Right:** Crusher site

4.2 Driving Forces

The two projects have similar motivations, akin to those from earlier projects [2]. At Brønnøy Kalk, a flexible solution for rock haulage was needed which could be tuned quickly to address the variable demand for limestone and increase operational efficiency. Once fully scaled, the mine can operate 24/7, decoupling the operation from contract worker availability and working hour regulations. The same is seen at OSL, where half of the ground services team are employed on 4–6-month winter contracts to ensure sufficient snow clearing capacity. Some are dispatched only during adverse weather. Hence, if conditions were to be favorable, Avinor pays for a service which was not needed. For both cases, such work is befitting for short-term contracts, but these are less appealing for workers. Besides, and especially at Brønnøy Kalk, recruitment is hard due to the remote location. Manual driving in the mine is dangerous, and, and accidents may happen.

At OSL, drivers currently require line-of-sight to the preceding truck, which may not be available in heavy snowfall, or may only be available at short separations. If runways are slippery, rear-end collisions may occur. The low speeds mostly cause material damage. Automation and coordinated fleet control are expected to reduce both the frequency and severity of collisions, and fewer occupants are present who can be injured. At OSL, automated operations are also more positionally accurate and repeatable, requiring smaller lateral overlaps between successive trucks. Automation removes the need for drivers being confined to the trucks for long periods, particularly at OSL during heavy snowfall, when breaks are scarce. Instead, drivers can switch between being the ASR operator and doing other tasks, e.g., at two-hour intervals, drawing inspiration from ATC shift structures. This may also improve safety and working conditions. Automation may also unlock staffing cost reductions. Earlier mining projects have cited 20% productivity gains and fewer safety incidents [2]. Automation may also allow for keeping the mine running and the runways open to facilitate flight movements, when, under manual operations, e.g., due to weather conditions or worker availability, they might otherwise have had to shut down, e.g., [50,51].

4.3 Organization

The trucks at Brønnøy Kalk are unoccupied, and they are managed by a wheel loader operator. He uses the wheel loader to transfer limestone between the stockpile and the trucks, and hence he oversees the trucks in person during loading. Between the quarry and the crusher, however, the trucks are fully driverless and beyond visual range of both the wheel loader and crusher operators, but are tracked en-route using a cloud system. In addition to overseeing the crusher, the crusher operator is in charge of administering access to the AOZ. The other automated trucks constitute most traffic encountered. In contrast, the ASR operator at OSL partakes in, and continuously oversees the operation using visual sight and a tablet in the lead truck. ATC administers all traffic, e.g., ground vehicles and flight movements. The platoon at OSL stops at predefined locations where the ASR operator requests runway access, and ATC acts as gatekeeper. Both use-cases have formalized roles and instructions for maintenance and support functions. Before the ASR project, ATC used printouts of snow clearing patterns and radio communication with the lead driver to divert flight movements. Now digitized, ATC can more tightly schedule flight movements adjacent to snow removal operations.

Both applications use staging areas to transition the trucks between manual and automated mode. Due to the technical differences between the solutions, however, staging areas serve slightly different purposes. At OSL, trucks are positioned and the automated system activated, while at Brønnøy Kalk, vehicles are parked at fixed spots where operators clean the sensors and control the trucks prior to system activation. During winter, the trucks at Brønnøy kalk are readied at a staging area inside a tunnel, shielding them from the elements. In both use-cases, lights on the truck roofs indicate that automated mode is active. At OSL, all trucks which comprise the platoon are started in batch, whereas at Brønnøy Kalk, they can be started and dispatched successively. Previously, trucks would approach the blast sites for loading. Since these locations frequently change as rocks are mined and hauled away, a stockpile was introduced to simplify the automated operation, decoupling it from shifting physical locations.

Both interviewees praised closed sites as enablers, serving to limit the effects of operational hiccups. Within these closed areas, however, different strategies were used to constrain the automated operation. The AOZ at Brønnøy Kalk is constrained physically using large, impenetrable stone blocks. Digital fences are also used, and the automated operation stops automatically if these are crossed. OSL uses no physical barriers between automated operations and other airside activities. ATC grants access to the area, and GNSS-based geofencing constrains the trucks, ceasing operations if breached. In case of system faults (e.g., cellular or GNSS fallouts) while the trucks are within their designated constrained areas, they stop automatically in both applications. Potential obstacles, however, are handled differently. The OSL trucks do not stop for obstacles automatically. Mainly the ASR operator, but also the snow removal manager and ATC, have the ability to stop them. The ASR operator monitors the immediate surroundings of the platoon, but he is unable to monitor in front of the following trucks. The platoon benefits from the fact that the runway, under any circumstances, must be kept free of objects to ensure the safety of flight movements. Hence, obstacle detection capabilities were considered unnecessary for the OSL trucks. The use-case at Brønnøy Kalk, on the other hand, more closely resembles conventional traffic on public roads. There, trucks are equipped with sensors to detect obstacles, for which the trucks will stop automatically. The wheel loader operator is alerted if a truck faces an obstacle, and a worker is dispatched to assist. Both interviewees stated that ensuring safety of personnel inside the constrained areas was challenging. For instance, at OSL, ASR operators exit the trucks during personnel swaps and for system rebooting, and at Brønnøy Kalk, refueling occurs within the AOZ.

During development, both applications used safety drivers in all trucks, to ensure that the trucks did not deviate from the assigned route or run into other trucks. While safety drivers were required at OSL at the time of the interview, Brønnøy Kalk had just undertaken their first unmanned production shift. The interviewees pointed out that precautions had to be taken since some technical systems were somewhat unreliable, especially during unforeseen circumstances. Both acknowledged that automation introduces vulnerabilities. As stated by the VAS interviewee:

"*Our solution is both more and less flexible at the same time. There will probably be more downtime with an automated solution than with a manual one. Maybe the automated solution can compensate by hauling more before or after snowfall, offsetting future downtime.*"

At Brønnøy Kalk, conservative speed limits were initially introduced to ensure safety drivers have sufficient time to intervene. Now that safety drivers have been removed, these will be gradually increased. A relative speed limit of 30 km/h is used, such that, in meeting lanes, speeds of opposing trucks are at most 15 km/h, but due to the site conditions, trucks are often unable to travel this fast anyway. At OSL, the operation runs at 30–40 km/h, as this is ideal for snow clearing. Hence, speeds in both use-cases are low. Seatbelts were previously not required for the trucks at OSL, as they are regulated as machines. However, automated fallback during system malfunctions had the trucks brake so harshly that safety drivers ran the risk of getting injured if unprepared, and seatbelts were mandated as a result. However, the system had been so reliable lately that there had also been cases of safety drivers falling asleep. Once fully operational, both use-cases need human fallback personnel. This is especially important at OSL, where Avinor delivers services which are more time-critical. While Brønnøy Kalk has partnered with a local haulage contractor, Avinor uses retrained drivers in support roles. If needed, they are dispatched to the unmanned follower trucks, where they continue driving manually. At OSL, it should take Avinor 20 minutes to get the service running again with manual drivers. Once the solution at Brønnøy Kalk is operational, fallback crews will be located off-site, and it is somewhat unclear how much lead time fallback would require.

4.4 Technology

Both cases depend on cellular connectivity. OSL has redundant communication with two separate carriers, while Brønnøy Kalk relies on one. Both sites were pre-mapped, but differently, allowing for different levels of operational flexibility. At Brønnøy Kalk, the route was manually driven whilst recording its lidar signature. The recording was subsequently distributed to all trucks, which use it to localize themselves in relation to their surroundings. The trucks follow a pre-defined route, and, if there are big changes to the surroundings, the recordings must be redone. In case the trucks encounter an obstacle along their route, these must be removed before resuming automated operations. In addition to lidar, GNSS navigation is used in the quarry, as it has line-of-sight to GNSS satellites. At OSL, on the other hand, GNSS is used exclusively for navigation, i.e., relying on no sensors. The airport was already pre-mapped with exact GNSS positions using aerial and satellite photos, at an accuracy sufficient for automated operations. Routes are drawn onto these images using software, and they are easy to adjust. Digital markers define positions where the platoon should stop and request ATC clearance, and where changes should be made to the plowing operation, e.g., turn wheel, increase speed or turn plow. Positional accuracy at OSL is 2–5 centimeters, versus 0.5 meters for manual plowing. Brønnøy Kalk did not provide a level of accuracy, but it is presumably similar. Both applications use Real-Time Kinematic (RTK) [52] base stations and subscribe to CPOS (centimeter positioning) [52] services from the Norwegian Mapping Authority, which allow GNSS receivers to calculate their position at centimeter-level accuracy [53]. Both applications use geofencing, they do so differently. The route at Brønnøy Kalk is divided into short segments which can only be inhabited by one truck at any given time. The same principle is used at OSL. There, traversable asphalt surfaces are divided into grid-sections, and planned operations must take place within them. The platoon stops automatically if any truck deviates from the grid.

The use-cases have different levels of susceptibility to bad weather due to the different requirements for perception. Both are unaffected by rain, light conditions and normal snowfall. Having no sensors which may become blinded, the OSL use-case is also robust to extreme snowfall. In fact, sensors would limit the performance of the system in such conditions, which also happen to be the periods where it is most critical for runway uptime. The lidars at Brønnøy Kalk, on the other hand, struggle with heavy snowfall. In winter, the temperature difference between inside and outside tunnels occasionally cause icing on the lidars. Dirt and dust also deposit on the glass, requiring cleaning, and the glass must withstand impacts with small rocks. The glass should not be scratched, so maintenance solutions should ideally not require physical touch. However, upon cleaning, the combination of dust and fluid makes the lidar blind, so they must be washed successively when in motion, or when stationary. Lidar reflector boards were installed in tunnels with insufficient texture. In winter, however, groundwater seeps through the tunnel roof, causing excessive ice build-up on boards, causing them to deform and fall down. Thus, trade-offs were made regarding which ones to keep, while maintaining sufficient positional accuracy and avoiding icing. Similarly, reflector walls outside get covered by snow, which must be removed. Naturally, snow removal is also needed to keep the road itself accessible. Reflector boards were raised to facilitate snow storage underneath them, but this placed them at odds with lidar operating heights in areas where trucks were slightly tilted. Condition monitoring and maintenance efforts had to be intensified, taking more time and resources than forecasted.

4.5 Regulations

Permits for testing the automated trucks at Brønnøy Kalk were issued by the NPRA, and the interviewee was positive in regards to their cooperation. In dialogue, it often became apparent that original regulations were no longer applicable, having been implemented to safeguard human health. This was taken to heart by the NPRA. The vehicle operators, who drive the trucks to and from the staging area and serve as fallback drivers, are required to have a driving license for trucks. At OSL, regulatory information for pilots and employees who may interact with the automated trucks, was updated, and the relevant authorities were briefed. The NPRA and the Civil Aviation Authority (CAA) discussed the matter and agreed that, since the trucks are not designed for public roads, the 2018 self-driving law does not apply. They are hence governed by the CAA, who granted Avinor approval subject to certain conditions, to run the operation without safety drivers. As previously mentioned, the machines are also governed by EU-level machine regulations.

4.6 Project Learnings

The projects came about in similar ways, after Brønnøy Kalk and Avinor contacted potential suppliers in the mid-2010s, asking whether they would be interested in delivering the solutions required for automation. Limited supplier interest resulted in both projects taking several years to materialize. Avinor had three interested suppliers, while Brønnøy Kalk had only one. The project at Brønnøy Kalk is a true commercial collaboration, although VAS covers much of the costs and risks involved, to "*learn about the commercial aspects involved*". In contrast, Avinor takes on both, procuring the services and technology from a supplier group. The interviewees recognized that, while their systems may seem simple, progress has taken significantly more time and resources than expected. System complexity creates a wide array of failure modes, and over time, a patchwork of components and solutions have been implemented, and interdependencies introduced, making troubleshooting difficult.

The digitalization of previously non-computerized operations had both interviewees stress the importance of change management. Bugs are uncovered in on-site testing and fixed in subsequent release candidates. Changes are frozen, and the new software is thoroughly tested and validated for stability in the field. Subsequent software versions may be written while the former is tested. At OSL, new software is tested on a few trucks first, before being rolled out to all six. For both use-cases, new releases require entering and updating all trucks separately, taking 15 minutes per truck. The VAS interviewee stressed the importance of on-site testing, as it is hard to foresee challenges caused by e.g., weather conditions and tunnels. Both stated that, once the operations were scaled up, software releases must be coordinated and scheduled for quiet periods, since they cause downtime. The systems are also more vulnerable to software problems once in full production, as suppliers may no longer be available on-site. The roll-out strategy also differed between the use-cases. At Brønnøy Kalk, conventional trucks keep operations running while the automated solution is gradually tested and implemented. At OSL, however, the same trucks are used for testing and operative snow removal, such that, if the automated system malfunctions, the trucks must be transferred to manual operation immediately to maintain appropriate runway conditions. The lower priority of debugging at Avinor, versus performing their core task, causes a drawn-out implementation period.

The software-driven development approach represented a change in mindset for both use-cases, in its requirement for highly systematic and formal control. Avinor arguably had a head start versus Brønnøy Kalk, in terms of having access to overarching processes which could be implemented from elsewhere in the organization. As stated by the Avinor representative: "*the aviation industry has been using advanced* *technology for decades. We are required to undertake change processes, carry out risk assessments and update the management system (…)*", reporting changes, including for automated snow removal, in an international ledger on 12 fixed dates yearly [54]. While IT personnel at Avinor were previously not involved in machine procurement, they had now become key resources involved in all project phases, from specifying requirements to testing and implementation. Both interviewees stated that risk assessments have been done, and that procurement from subcontractors included cyber-security requirements and compliance testing. Both underlined the importance of having a cross-disciplinary team with a combination of technical and communication skills to spearhead such efforts. This is especially the case for Avinor. Across all shifts, around 150 airside employees will be present alongside the automated trucks, versus 10-15 at Brønnøy Kalk. As stated by the Avinor interviewee: "*This is a communication project, more than a technology project*". Both also championed for a first-principles approach, identifying the least complex technical and organizational way of solving the problem, e.g., excluding sensors and thus associated failure modes, where possible. Both stressed the importance of trust between the supplier and the client for achieving cooperation.

When asked whether the OSL system could be repeated at other airports, the interviewee stated that some testing could be skipped, as the trucks and control platform could be reused. However, processes related to verification and employee training, which were significant, must largely be repeated, due to regulatory aviation requirements. In fact, each airport must "*(…) apply to the Civil Aviation Authority to have the automated [snow removal] system reflected in its certificate*". VAS pointed out that all the learnings from Brønnøy Kalk are being used in designing the technical solutions for future locations and customers.

5. Reflections for Open Roads

This section reflects on insights from the interviews, relating them to the introduction of automated trucks on open roads. Parts of the reflection are also relevant for all automated vehicles. The use-cases show that shortcomings in infrastructure, technology and regulations can be overcome by organizational means [2].

5.1 Automation Levels

The target automation level differentiate the use-cases [20]. Both lie between SAE levels 3 and 4, based on whether fallback is assigned to a human operator (levels 1–3), or if the trucks remain in control and achieve a minimal risk condition when required (levels 4–5) through emergency stops or careful driving [2,55]. At OSL, the ASR operator mans the lead truck in the platoon, placing it at SAE level 3. The followers are unmanned, i.e., level 4, but are overseen by the ASR operator, who also has the authority to stop the trucks if needed. The lowest common denominator places the use-case at level 3. At large, the SAE scale is a poor fit for platoons [20], which may be comprised of trucks with several automation levels [43]. The OSL use-case is perhaps better described by function K of the concept alternatives defined by [22]. Brønnøy Kalk is more clearly a SAE level 4 system, as trucks are unmanned and responsible for immediate fallback. The wheel loader and crusher operators are the only humans involved, but they do not visually oversee the operation beyond their immediate surroundings. Like the ASR operator, the wheel loader operator is essential to the operation, so the two systems are similarly organized. Both interviewees cited the ability of their trucks to be transferred to manual mode to resume operations as a key strength for redundancy and flexibility.

5.2 Control and Oversight

Both use-cases have distributed control and oversight, and the three hierarchical levels of the driving task may serve as a conceptual framework [20,56]. At OSL, strategical tasks, i.e., overarching planning, are performed by ATC, a shift leader and the snow clearing manager. Tactical tasks, i.e., high-level maneuvering, are jointly overseen by the snow clearing manager and ASR operator. Operational tasks, including continuous lateral and longitudinal control, are performed by the automated system, with the ASR operator for direct fallback. At Brønnøy Kalk, strategical and tactical roles are handled jointly by both the crusher and wheel loader operator, in their respective roles as gatekeeper and dispatcher. The operational task at Brønnøy Kalk, however, is fully automated. The complexity of on-road traffic is significantly higher than in the two use-cases. Inspired by OSL, automated vehicles on public roads could be managed on the strategical level by a central coordinator with oversight of all actors. The NPRA operates five 24/7 traffic control centers which monitors the road network, handles incidents and provides information to the general public [57]. Future work could explore whether these could be repurposed and their mandates broadened to handle traffic coordination for automated vehicles [58]. Perhaps carriers, as they now do, could serve the tactical role, adding to existing infrastructure for logistics coordination. Lastly, trucking automation systems with elements from both use-cases could handle the operational level. Having a central strategical coordinator may also facilitate improvements before full automation is unlocked. For instance, the unlocking of tighter flight timing by ATC in the wake of automated snow clearing, resembles the benefits which may be obtained by V2V-communication on roads, where better coordination can minimize time loss, e.g., in traffic signals. From a technical perspective, the Avinor interviewee noted that the ASR operator could have administered the platoon from elsewhere, but for safety reasons, it was chosen to have him located in the first truck.

Both use-cases simply shut down in case of outages. While appropriate for closed-site applications, this is not applicable for open roads. A distributed system, where each automated vehicle acts independently of the others, i.e., takes on all hierarchical planning levels, would likely be harder to implement, but also more resistant to faults. Since trucks fail independently, Brønnøy Kalk might be a better model, as faults at OSL would cause the whole operation to stop. Potential breakdowns at Brønnøy Kalk are serious, but they affect a limited number of individuals and customers. The impacts are more severe at OSL, and the Avinor interviewee provided estimates of delay costs during snow removal downtime leading to runway closures. As airports are also critical infrastructure, and since airlines have formalized delay pricing, at 1000 NOK per minute, these conceptualize the costs of downtime in an automated road freight system. Assuming OSL closes for 8 hours, 750 flight movements are affected, totaling 360 million NOK, excluding the value-of-time of delayed passengers. A rigorous analysis would include this delay, and it would presumably show that delays on major roads due to malfunctions in automation would get very expensive, let alone dangerous to public safety, as they would presumably affect all traffic and not just road freight. Hence, higher levels of reliability and uptime are required of the systems facilitating automated road transport.

5.3 Ownership

While roles in road freight are more fragmented, e.g., vehicle and infrastructure ownership, maintenance and traffic coordination, these interfaces are simple in the use-cases, having only one infrastructure owner and only one or two main suppliers. At OSL, Avinor is in charge of vehicles and infrastructure, and, while Brønnøy Kalk has separate infrastructure and trucks owners, it is still only two parties. Hence, reducing the number of stakeholders may be seen as an enabler for automation. Automated trucks for public roads will likely be provided by multiple suppliers, which must adhere to standards for both roadway design and digital architecture. While highly simplified in comparison, the two use-cases suggest that the road freight industry may be subject to consolidation as automation is introduced.

5.4 People

Both cases used safety drivers during testing, and had to employ measures to keep them safe. Brønnøy Kalk introduced slow speed limits to ensure that they had sufficient time to intervene, and Avinor mandated seatbelts to keep them safe during harsh automated stops. During prolonged flawless operation, Avinor cited cases of safety drivers falling asleep. These examples illustrate the difficulty of level 3 systems, whereby situational awareness requirements for human operators are unclear [20]. The Avinor representative cited difficulties for defining criteria for when safety drivers could be removed. Stated otherwise: "*the system must always work, otherwise drivers must be present*" (VAS). Hence, even quite capable systems which handle multi-hour drives flawlessly [59], are labelled as SAE level 2, since interventions occasionally occur, which warrant supervision. This may partly explain why automakers often denote ADAS systems as "SAE level 2.5" [21]. When "*previously manual tasks are replaced by surveillance and monitoring*" (VAS), "*road traffic should be very concerned with safety drivers becoming passive*" (Avinor), as this may impact traffic safety. SAE levels may be confusing, as they are described technically, but defined by their need for human supervision [21]. The scale is coarse, and it does not capture the development process required to advance between levels. A new classification may account for organizational aspects, e.g., whether vehicles within a platoon or a broader system are partly controlled or observed by occupants in different vehicles or remotely. Roads authorities should also consider approaching automation practically, e.g., setting thresholds for the number of interventions per time or distance which are allowed in different infrastructure, traffic and weather environments, running them through standardized or randomized test conditions.

The VAS representative stated that ensuring human safety during breakdown events will be especially challenging on public roads. As automated systems scale, actors other than users and employees who are familiar with them will increasingly have to interact with them. Brønnøy Kalk has held exercises with the fire brigade to inform them how to behave around the trucks. Laminated sheets on the trucks inform others how to approach them. He also pointed out that it is comparatively simple to organize training for local external actors. Over longer distances, e.g., for automated trucks on public roads, procedures must be intuitive, or adequate explanations provided, to ensure safe human-vehicle interaction. A range of stakeholders will need this information as roadway automation proliferates, so it should also be standardized across manufacturers and suppliers. In an SAE level 3 system, e.g., Avinor, the sustained presence of the ASR operator may reduce the need for such information.

At Brønnøy Kalk, employees entering the AOZ wear portable emergency stops, which, if activated, stops all trucks in operation. Such buttons are currently not used at Avinor. Hence, occupants are not allowed to leave their truck during automated operation. Automated vehicles must be able to detect people and obstacles and to stop on their own. Hence, the functionality of the trucks at Brønnøy Kalk for detecting obstacles is more appropriate. In parking lots and similar locations, humans are very vulnerable, and must somehow be ensured of the behavior of automated trucks. In traffic situations, they should also exert caution and yield or stop automatically. Automated vehicles must be tested to such a rigorous extent that they can handle most foreseeable situations. Considering the timeline of the two use-cases herein, such testing will be immensely resource-intensive. The MODI project is a step in the right direction, but more work is needed in parallel to facilitate developments. Some have suggested running unmanned freight along a designated road network [60], to reduce complexity, but in practice this seems infeasible.

5.5 Electrification and Autonomy

The interviewees cited pressure towards electrification, but due to high power demands, this is not yet profitable. At Brønnøy Kalk, substitution of diesel trucks for electric ones would reduce per-truck hauling capacity, and require charging, such that many more electric trucks would be needed to perform the same transportation. Trucks are currently made as large as permitted, maximizing per-driver output. The VAS interviewee stated that unmanned operations changes the objective, so they can be made smaller, enabling electrification. In the future, such use-cases, and possibly also road freight, could be solved by a larger number of small pods, carrying e.g., 5 metric tons each, as opposed to e.g., 60 metric tons today. Likewise, the Avinor interviewee imagined snow removal at small airports using small, self-dispatching autonomous machines which operate continuously during snowfall, as opposed to having large, human-driven ones which currently operate intensively the in last few hours before flights. Electrification of trucks is in its infancy, e.g., [61,62], and while battery cost declines will further the trend, downsizing and autonomy could be accelerators, also warranting a holistic approach to both automated trucks and passenger cars together.

5.6 Infrastructure

The site at Brønnøy Kalk resembles rural, public roads, exemplifying feasible solutions for GNSS-denied areas. The VAS representative acknowledged that their use of stone barriers has low relevance for public roads: "*This works well on enclosed areas, but on public roads we cannot build stone barriers and run traffic at very low speeds. We work (…) to achieve redundancy in the most important functions, but still, the redundancy here is stone barriers*.". Nevertheless, digital fences may add to traditional guardrails, automatically alerting and stopping traffic within some vicinity of roadway departures. The lane classification at Brønnøy Kalk also has merit, allowing automated traffic to be coordinated such that opposing trucks meet on suitable sections.

Automation of road transport may require trade-offs or redesign of adjacent processes. Akin to the stockpile, checkpoints and staging areas, transition zones may facilitate switching between manual and automated mode [3,22] on main roads with limited-access. Perhaps suitably located gas stations could be used for this purpose. Vehicles could stop or traverse them slowly, resembling tolling operations. For instance, sensors could be cleaned, and software and maps updated and verified. Overhead gantries may also be used to calibrate on-board equipment while driving [3]. Road users may also be mandated to document the state of the vehicle and verifying software and mapping status, resembling smartphone applications for car sharing. For Avinor, expansion of ASR to new airports require each one to have its regulatory certificate updated. Perhaps the same idea could be used for road sections for automated vehicles, where appropriate road owners would have to apply for a permit showing that the road satisfies a readiness standard, resembling the permitting of the 25-meter European Modular System road trains [1]. In Norway, the general speed limit outside urban areas is 80 km/h [63]. Hence, operating speeds for the two use-cases are below those which automated trucks would need to maintain on most open roads. As at Brønnøy Kalk, driving speeds could rise as a function of proven system reliability, but for automated freight, they could also remain lower than current speed limits, as the added cost of slower freight could be counteracted by lower operating costs.

Icing on lidars at tunnel entrances may perhaps be avoided using chemicals, electrical heating or by funneling residual heat from the engine bay using pipes. However, trends for electrification go against the latter, and tunnel portals may be fitted with hot air pumps instead. The use-cases are also different in the temporal consistency of their ODDs. While the ODD at Avinor are sustained winter conditions, Brønnøy Kalk must handle all seasons. This is difficult, exemplified by snowfall altering the surroundings and undermining lidar localization. This will also be the case for automated vehicles on public roads. Hence, solutions should account for changing ODDs. Tunnel design standards for open roads are more stringent than those at Brønnøy Kalk, so the issue of groundwater seepage and subsequent ice build-up is less likely to occur. However, perhaps modern tunnel designs with spherical concrete rock walls coverings, which have fewer contours, are more difficult for lidar-based navigation, requiring more adaptation for accurate localization. If roads and tunnels are to be equipped with roadside infrastructure, it should be consistent and standardized. In any case, road design and maintenance requirements for automated vehicles must be studied further.

5.7 Technology and Software

On open roads, any number of situations may require deviations from the planned trajectory. Hence, the framework of Brønnøy Kalk, whereby routes are fixed, both longitudinally and laterally, would not work. Since routes are not varied laterally, road wear would be excessive, and the VAS interviewee stating that Brønnøy Kalk had asked for this functionality. An adaptation of the Avinor approach, drawing geofencing grids and visualizing routes on high-definition maps or aerial images, seems superior in terms of intuitiveness and flexibility, and could work in tunnel-free areas. Map data is widely available in Norway, and it should be investigated whether the current repository holds sufficient quality to be used directly. While no small task, it should be feasible to instrument all tunnels with beacons, reflector walls or other infrastructure if this is needed for automated vehicles to traverse them, as they comprise only 1.6% of the Norwegian public road network [16,64]. Successive trucks could be offset laterally in a randomized way to lessen pavement wear. The Avinor interviewee stated that, functionally, aerial photography and GNSS positioning would work for driving the trucks along normal roads. The quality of cellular communication along opens roads is poor at times, and its sufficiency for automation should be verified. Tunnels hinder GNSS positioning, and would cause the operation, in its current form, to break down. Ensuring GNSS positioning is important [3], and since both cases depend on it, the CPOS service could be scaled up to accommodate future use in automated road system. In fact, Avinor is considering expanding the number of GNSS base stations, allowing for triangulation in case of outages. This representative also expressed optimism towards the Starlink satellite constellation, e.g., [65,66], and how it may improve data volume capacity, reduce latency and mitigate outages, while reducing the need for establishing and maintaining fixed infrastructure. Sensors for on-road automation should be robust and able to successively self-wash, so driving does not need to stop. As stated by the VAS interviewee: "*Lidars become the windscreen of the car. The automation system cannot roll down the window and peek outside*". It is also likely that an automated road system will be more susceptible to bad weather, placing higher demands on accurate and reliable long-term weather forecasting.

Automated road transport will require software updates. As opposed to at Avinor, however, these should not occur simultaneously for all vehicles, as it would disrupt traffic. This makes change management important. Updates with different levels of criticality could be distributed at different levels of urgency. For those that require downtime, users could be given reasonable deadlines by which to comply, upon expiry of which the system does so automatically. Updates to e.g., a map of a road section which the vehicle is not currently occupying, could perhaps occur in real-time. The Avinor representative stated that a central information system is critical for seamless operation, and that "*road transport has a lot to learn from aviation. The aviation industry is slow to change, but we have been using advanced technology for a very long time*".

6. Conclusions

This paper reported learnings from two use-cases of automated trucks on closed areas, one at an airport, and one at a limestone mine. They illustrate well the struggles which are forecast to manifest when automating road freight and vehicles in general, on public roads. Both applications are behind their original deadlines, having faced unforeseen technical, infrastructural and organizational challenges.

While research on automated vehicles is well underway, both in industry and in academia, the issues faced by these two use-cases suggest that there are still many challenges which have not yet been conceived of. Based on their knowledge, both interviewees expressed skepticism towards implementing automated trucks and vehicles on public roads. Still, parts of each solution could serve as meaningful building blocks for an automated road transport system. For instance, the object detection and in-tunnel localization framework from Brønnøy Kalk could be coupled with the intuitive and user-friendly planning tool from Avinor, alongside their redundant cellular communication system. Staging areas could be used to verify the readiness of vehicles for entering approved road stretches, using a regulatory approach inspired by airport certificates, and traffic coordination could be handled by traffic control centers or carriers, inspired by air traffic control.

In both respective use-cases, operational responsibilities for all parts of the automated system were formalized through documentation and protocols. Already used to stringent process control, Avinor had a notable advantage. While it is underway, this development occurring in the road transport system will likely take significant time, as it involves far more stakeholders which must work together. Hence, as pointed out by the interviewees, communication is key. Moreover, software culture and change management represents a paradigm shift for many involved. One must also remember that professional drivers have a significant knowledge-base which must to some extent be duplicated by ADSs to achieve redundancy. Fallback in an automated road system is also sill very unclear, and hence, any changes made to accommodate automated vehicles should not compromise manual driving, and also since many SAE levels will likely co-exist for decades. The introduction of digital tools can also meaningfully improve auxiliary processes, unlocking benefits before full automation is possible.

We urge stakeholders pursuing vehicle automation, even in what seem like disparate fields, to collaborate. Roads authorities should fund more on-road testing and research efforts, partnering with academia to share the learnings. As the interviewees alluded to, dedicated arenas could be established, enabling controlled and systematic AV testing. The Avinor representative succinctly summarized the most relevant and transferrable lessons from his use-case to automation of road freight:

> "*The most relevant experiences relate to the interfaces between process, human and machine. The system must account for the total competence of the truck driver, much of which is tacit. Winter conditions are very demanding, so automated solutions must be backed up by road maintenance and redundant communication and positioning systems*."

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