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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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