Denne artikel er udgivet i det elektroniske tidsskrift
Artikler fra Trafikdage på Aalborg Universitet
(Proceedings from the Annual Transport Conference at Aalborg University)
ISSN 1603-9696
https://journals.aau.dk/index.php/td

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

Markus Metallinos Log[1], markus.log@ntnu.no
Maren Helene Rø Eitrheim[1,2], maren.eitrheim@ntnu.no
Kelly Pitera[1], kelly.pitera@ntnu.no
Trude Tørset[1], trude.torset@ntnu.no
Tomas Levin[3], tomas.levin@vegvesen.no
[1]Norwegian University of Science and Technology (NTNU)
[2]Institute for Energy Technology (IFE)
[3]Norwegian Public Roads Administration (NPRA)

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.

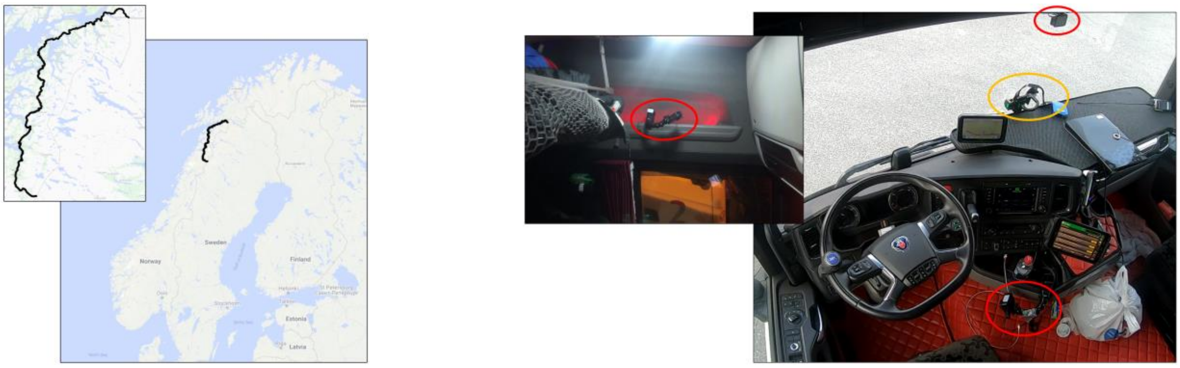
The vehicle could interfere with the platooning system through traction control (1), downhill speed control (2) and eco-roll (3). The truck would automatically disable the system in low-friction situations, until detecting sufficient friction again. In the meantime, the driver would need to perform longitudinal 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.

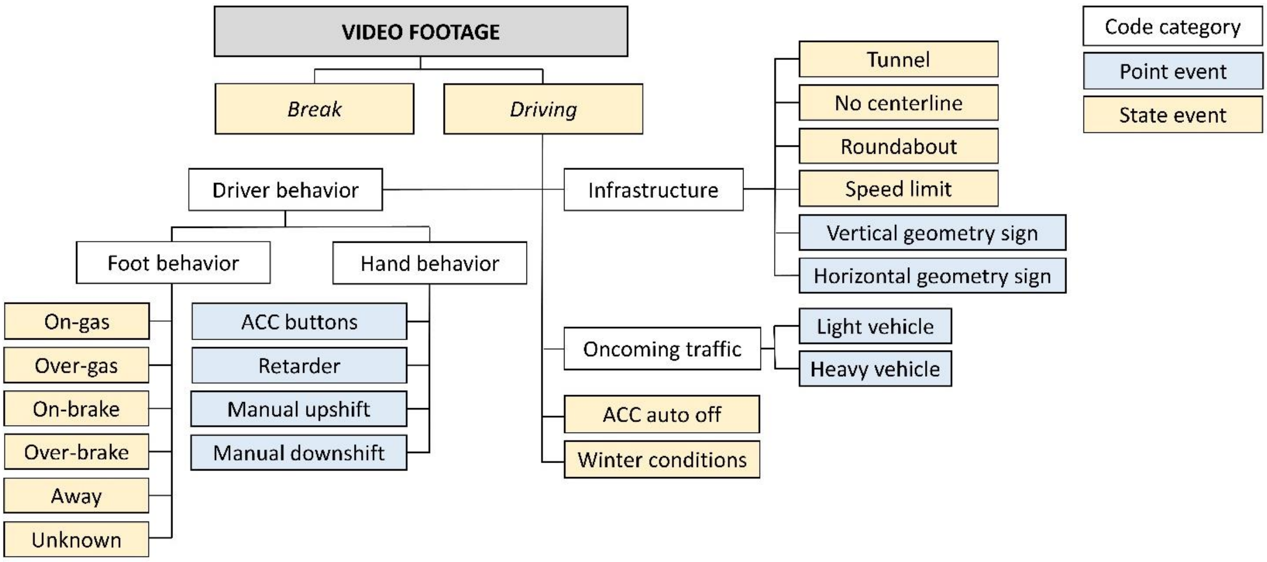


Figure 1: Overview of BORIS annotations.

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.

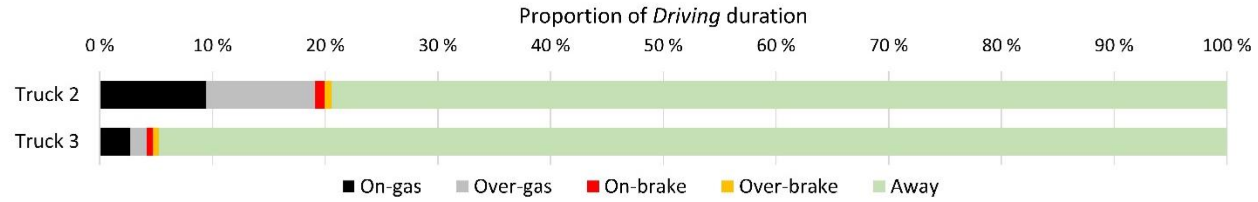


Figure 3: Proportions of driving duration for foot behaviors for the two followers.

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.

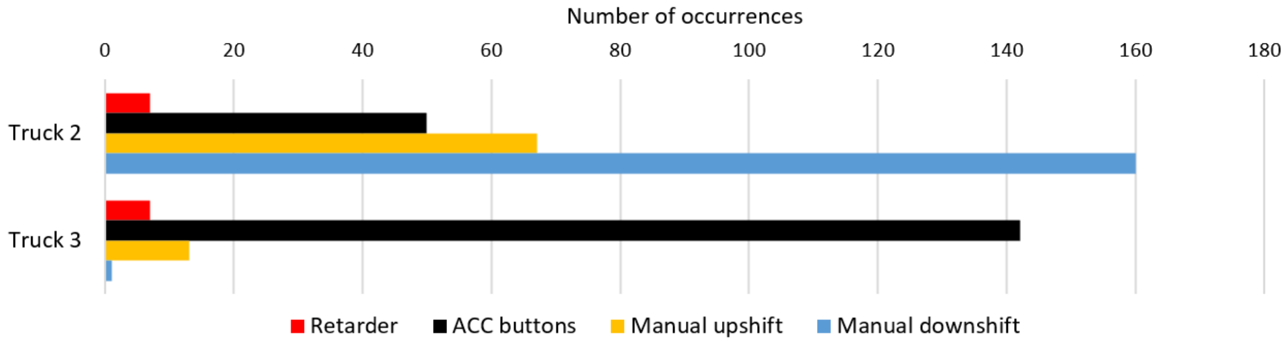


Figure 4: Number of hand behaviors for the two followers.

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.

References

1. Zhang, L.; Chen, F.; Ma, X.; Pan, X. Fuel Economy in Truck Platooning: A Literature Overview and Directions for Future Research. *Journal of Advanced Transportation* **2020**, *2020*, e2604012, doi:10.1155/2020/2604012.
2. Tsugawa, S.; Jeschke, S.; Shladover, S.E. A Review of Truck Platooning Projects for Energy Savings. *IEEE Transactions on Intelligent Vehicles* **2016**, *1*, 68–77, doi:10.1109/TIV.2016.2577499.
3. Asare, S.; Chang, J.; Staples, B.L.; Noblis, Inc. *Truck Platooning Early Deployment Assessment– Independent Evaluation: Performance Measures for Evaluating Truck Platooning Field Deployments*; 2020;
4. Robinson, T.; Coelingh, E. Operating Platoons On Public Motorways: An Introduction To The SARTRE Platooning Programme. *17th World Congress on Intelligent Transport Systems, Busan, Korea, 25-29 October 2010.* **2010**.
5. Truck Platooning | California Partners for Advanced Transportation Technology Available online: https://path.berkeley.edu/research/connected-and-automated-vehicles/truck-platooning (accessed on 28 March 2023).
6. Automated Platooning – Step by Step Available online: https://www.scania.com/group/en/home/newsroom/news/2018/automated-platooning-step-by-step.html (accessed on 28 March 2023).
7. Platooning Project: DB Schenker & MAN Available online: https://www.mantruckandbus.com/en/innovation/why-platooning-is-the-future-of-delivery-traffic.html (accessed on 28 March 2023).
8. Aarts, L.; Feddes, G. European Truck Platooning Challenge. *International Symposium on Heavy Vehicle Transport & Technology* **2016**, 9.
9. Sturm, T.; Krupitzer, C.; Segata, M.; Becker, C. A Taxonomy of Optimization Factors for Platooning. *IEEE Transactions on Intelligent Transportation Systems* **2021**, *22*, 6097–6114, doi:10.1109/TITS.2020.2994537.
10. Lu, X.-Y.; Shladover, S.E. Automated Truck Platoon Control and Field Test. In *Road Vehicle Automation*; Meyer, G., Beiker, S., Eds.; Lecture Notes in Mobility; Springer International Publishing: Cham, 2014; pp. 247–261 ISBN 978-3-319-05990-7.
11. Penttinen, M.; van der Tuin, M.; Farah, H.; Homem de Almeida Correia, G.; Wadud, Z.; Carsten, O.; Kulmala, R. *Impacts of Connected and Automated Vehicles - State of the Art*; MANTRA: Making full use of Automation for National Transport and Road Authorities – NRA Core Business; Conference of European Directors of Roads (CEDR), 2019; p. 63;.
12. Eitrheim, M.H.R.; Log, M.M.; Tørset, T.; Levin, T.; Pitera, K. Opportunities and Barriers for Truck Platooning on Norwegian Rural Freight Routes. *Transportation Research Record* **2022**, *2676*, 810–824, doi:10.1177/03611981221076438.
13. Global Driver Shortages: 2022 Year in Review Available online: https://www.iru.org/news-resources/newsroom/global-driver-shortages-2022-year-review (accessed on 2 May 2023).
14. Kashani, A.T.; Mohaymany, A.S. Analysis of the Traffic Injury Severity on Two-Lane, Two-Way Rural Roads Based on Classification Tree Models. *Safety Science* **2011**, *49*, 1314–1320, doi:10.1016/j.ssci.2011.04.019.
15. Haq, M.T.; Farid, A.; Ksaibati, K. Estimating Passing Sight Distances for Overtaking Truck Platoons – Calibration and Validation Using VISSIM. *International Journal of Transportation Science and Technology* **2022**, *11*, 255–267, doi:10.1016/j.ijtst.2021.03.009.

16. Garcia, A.; Pastor-Serrano, D. Determination of Minimum Horizontal Curve Radius for Safe Stopping Sight Distance of Vehicles Overpassing Truck Platoons. *Computer-Aided Civil and Infrastructure Engineering* **2022**, *37*, 539–557, doi:10.1111/mice.12758.
17. Haugland, B.T.; Ryghaug, M.; Søraa, R.A. Framing Intelligent Transport Systems in the Arctic: Reindeer, Fish and the Engineered Road. *Engineering Studies* **2023**, *15*, 50–70, doi:10.1080/19378629.2023.2169612.
18. Carreras, A.; Daura, X.; Erhart, J.; Ruehrup, S. *Road Infrastructure Support Levels for Automated Driving*; 2018;
19. Farah, H.; Erkens, S.M.J.G.; Alkim, T.; van Arem, B. Infrastructure for Automated and Connected Driving: State of the Art and Future Research Directions. In Proceedings of the Road Vehicle Automation 4; Meyer, G., Beiker, S., Eds.; Springer International Publishing: Cham, 2018; pp. 187–197.
20. Dysvik, E.; Homleid, T.; Andreev, L. *Kvaliteten på det norske veinettet*; Vista Analyse AS: Oslo, 2020;
21. Stone, T. Norway Opens E8 Borealis C-ITS Testbed with Truck Platooning Demonstration. *Traffic Technology Today* 2018.
22. Storsæter, A.D.; Pitera, K.; McCormack, E. Using ADAS to Future-Proof Roads—Comparison of Fog Line Detection from an In-Vehicle Camera and Mobile Retroreflectometer. *Sensors* **2021**, *21*, 1737, doi:10.3390/s21051737.
23. Shladover, S.E. Truck Automation Operational Concept Alternatives. In Proceedings of the 2010 IEEE Intelligent Vehicles Symposium; June 2010; pp. 1072–1077.
24. SAE Levels of Driving Automation™ Refined for Clarity and International Audience Available online: https://www.sae.org/site/blog/sae-j3016-update (accessed on 1 March 2023).
25. Lee, C.W.; Nayeer, N.; Garcia, D.E.; Agrawal, A.; Liu, B. Identifying the Operational Design Domain for an Automated Driving System through Assessed Risk. In Proceedings of the 2020 IEEE Intelligent Vehicles Symposium (IV); October 2020; pp. 1317–1322.
26. Taylor, A.H.; Droege, M.J.; Shaver, G.M.; Sandoval, J.A.; Erlien, S.; Kuszmaul, J. Capturing the Impact of Speed, Grade, and Traffic on Class 8 Truck Platooning. *IEEE Transactions on Vehicular Technology* **2020**, *69*, 10506–10518, doi:10.1109/TVT.2020.3009489.
27. McAuliffe, B.; Croken, M.; Ahmadi-Baloutaki, M.; Raeesi, A. Fuel-Economy Testing of a Three-Vehicle Truck Platooning System. **2017**.
28. Vartdal, T.; Ustvedt, T.; Marskar, E.-M.; Lysgård, H.; Vingan, A.; Drösemeyer, H.; Gjersum, H.; Bjørlykke, C.; Frostis, A.; Askildsen, T.C. *Nasjonal Transportplan 2022-2033 Godstransport- et Oppdatert Kunnskapsgrunnlag*; Arendal, 2020; p. 52;.
29. Gifstad, U.M.; Eikenes, S.; Baum, C.; Lunde, S.; Wangsvik, F.; Holt, A.G. *Konseptvalgutredning (KVU) for transportløsninger i Nord-Norge*; 2021;
30. Norwegian Public Roads Administration (NPRA) Handbook V120: Premises for Geometric Design of Roads 2019.
31. Norwegian Public Roads Administration (NPRA) Handbook N100: Road and Street Design Available online: https://store.vegnorm.vegvesen.no/n100 (accessed on 2 May 2023).
32. Pekkala, V.; Sorvisto, M.; Heikkilä, R. Expectations for Finnish Road Infrastructure in Semi-Automated Truck Platooning - Project Results. *Proceedings of 8th Transport Research Arena TRA 2020, April 27-30, 2020, Helsinki, Finland* **2020**.
33. Eitrheim, M.H.R.; Log, M.M.; Tørset, T.; Levin, T.; Nordfjærn, T. 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)*, 8.
34. Log, M.M.; Thoresen, T.; Eitrheim, M.H.R.; Levin, T.; Tørset, T. Using Low-Cost Radar Sensors and Action Cameras to Measure Inter-Vehicle Distances in Real-World Truck Platooning. *Applied System Innovation* **2023**, *6*, 55, doi:10.3390/asi6030055.
35. Forskrift Om Kjørende Og Gående Trafikk (Trafikkregler) - Lovdata Available online: https://lovdata.no/dokument/SF/forskrift/1986-03-21-747 (accessed on 4 July 2023).
36. Bergenhem, C.; Shladover, S.; Coelingh, E.; Englund, C.; Tsugawa, S. *Overview of Platooning Systems*; 2012;

37. Hilgers, M. Vehicle Technology. In *Fuel Consumption and Consumption Optimization*; Hilgers, M., Ed.; Commercial Vehicle Technology; Springer: Berlin, Heidelberg, 2023; pp. 13–43 ISBN 978-3-662-66449-0.
38. How to Use the Truck's Kinetic Energy to Save Fuel Available online: https://www.scania.com/group/en/home/newsroom/news/2018/how-to-use-the-trucks-kinetic-energy-to-save-fuel.html (accessed on 11 May 2023).
39. Kersting, S.; Hansen, L.M. Planprogram for E6 Sommerset-Mørsvikbotn – Høringsutgave 2022.
40. Norwegian Public Roads Administration (NPRA) E6 Megården-Mørsvikbotn Available online: https://www.vegvesen.no/vegprosjekter/europaveg/e6sorfold/ (accessed on 28 March 2023).
41. Håndbok N500 - Tunneler Available online: https://www.vegvesen.no/fag/publikasjoner/handboker/handboker-etter-hovedtema/tunneler/ (accessed on 7 July 2023).
42. Brovold, T. Ser ut som gruvesjakt Available online: https://www.nrk.no/nordland/ser-ut-som-gruvesjakt-1.10998800 (accessed on 28 March 2023).
43. Skogen, B.; Østensen, M. *Rapport: KS2 E6 Megården-Mørsvikbotn*; 2021; p. 56;.
44. Chen, D.; Ahn, S.; Chitturi, M.; Noyce, D. Truck Platooning on Uphill Grades under Cooperative Adaptive Cruise Control (CACC). *Transportation Research Part C: Emerging Technologies* **2018**, *94*, 50–66, doi:10.1016/j.trc.2017.08.025.
45. Ma, K.; Wang, H.; Zuo, Z.; Hou, Y.; Li, X.; Jiang, R. String Stability of Automated Vehicles Based on Experimental Analysis of Feedback Delay and Parasitic Lag. *Transportation Research Part C: Emerging Technologies* **2022**, *145*, 103927, doi:10.1016/j.trc.2022.103927.
46. Jackson, J.; Davis, B.; Gebre-Egziabher, D. A Performance Assessment of Low-Cost RTK GNSS Receivers. In Proceedings of the 2018 IEEE/ION Position, Location and Navigation Symposium (PLANS); April 2018; pp. 642–649.
47. Scania Fleet Management System Available online: https://www.scania.com/no/no/home/services/data-driven-services/fleet-management.html (accessed on 7 July 2023).
48. GoPro, Inc. *GoPro Hero 9 Black - User Manual*; GoPro, Inc.; p. 73;.
49. Dhakal, K. NVivo. In *NVivo*; Resource Review; ournal of the Medical Library Association: Ohio State University, Columbus, OH, 2022; Vol. Vol. 110 No. 2 (2022): April 2022, p. 3.
50. Friard, O.; Gamba, M. BORIS: A Free, Versatile Open-Source Event-Logging Software for Video/Audio Coding and Live Observations. *Methods in Ecology and Evolution* **2016**, *7*, 1325–1330, doi:10.1111/2041-210X.12584.
51. Mossi, J.M.; Albiol, A.; Albiol, A.; Oliver, J. Ground Truth Annotation of Traffic Video Data. *Multimed Tools Appl* **2014**, *70*, 461–474, doi:10.1007/s11042-013-1396-x.
52. Stapel, J.; Gentner, A.; Happee, R. On-Road Trust and Perceived Risk in Level 2 Automation. *Transportation Research Part F: Traffic Psychology and Behaviour* **2022**, *89*, 355–370, doi:10.1016/j.trf.2022.07.008.
53. SINTEF Energimodul Available online: https://mobilitet.sintef.no/energimodul/ (accessed on 6 July 2023).
54. Tsugawa, S. An Overview on an Automated Truck Platoon within the Energy ITS Project. *IFAC Proceedings Volumes* **2013**, *46*, 41–46, doi:10.3182/20130904-4-JP-2042.00110.
55. Singh, P.; Sharma, S.; Nandi, S.; Singh, R.; Nandi, S. *Leader Election in Cooperative Adaptive Cruise Control Based Platooning*; 2018; p. 14;.
56. Zhang, L.; Chen, F.; Ma, X.; Pan, X. Fuel Economy in Truck Platooning: A Literature Overview and Directions for Future Research. *Journal of Advanced Transportation* **2020**, *2020*, e2604012, doi:10.1155/2020/2604012.
57. Díaz-Ramirez, J.; Giraldo-Peralta, N.; Flórez-Ceron, D.; Rangel, V.; Mejía-Argueta, C.; Huertas, J.I.; Bernal, M. Eco-Driving Key Factors That Influence Fuel Consumption in Heavy-Truck Fleets: A Colombian Case. *Transportation Research Part D: Transport and Environment* **2017**, *56*, 258–270, doi:10.1016/j.trd.2017.08.012.

58. Lov Om Vegtrafikk (Vegtrafikkloven) - Lovdata Available online: https://lovdata.no/dokument/NL/lov/1965-06-18-4 (accessed on 3 August 2023).
59. Norwegian Public Roads Administration (NPRA) Kriterier for fartsgrenser Available online: https://www.vegvesen.no/fag/fokusomrader/trafikksikkerhet/kriterier-for-fartsgrenser/ (accessed on 3 July 2023).
60. Norwegian Public Roads Administration (NPRA) Vegkart Available online: https://vegkart.atlas.vegvesen.no/ (accessed on 28 March 2023).

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.

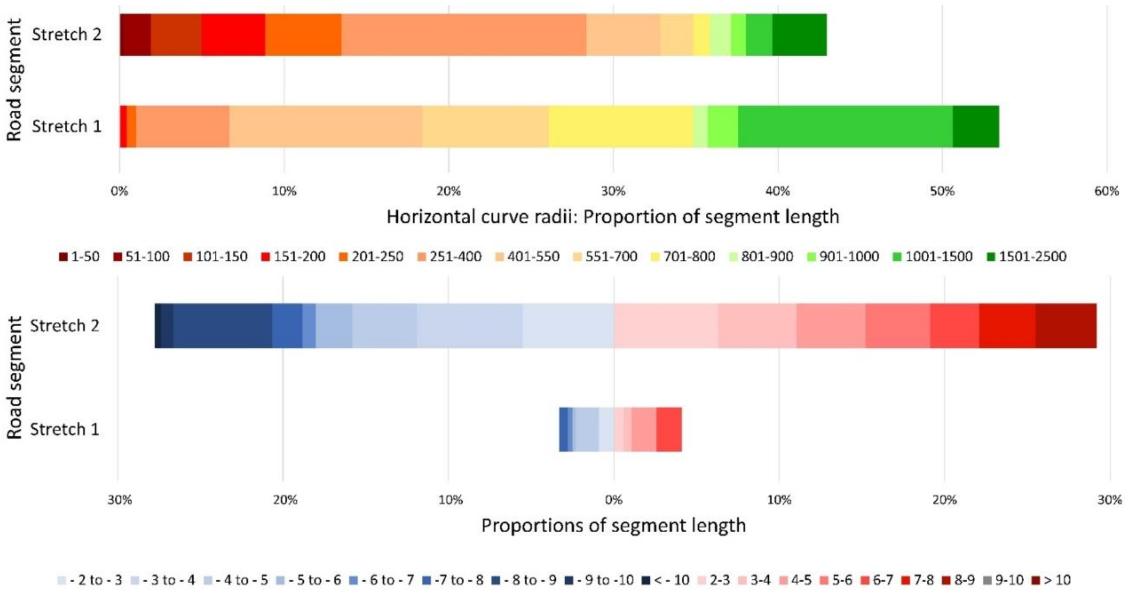


Figure A1: Proportion of horizontal curve radii (top) and vertical gradients (bottom) for the two stretches.

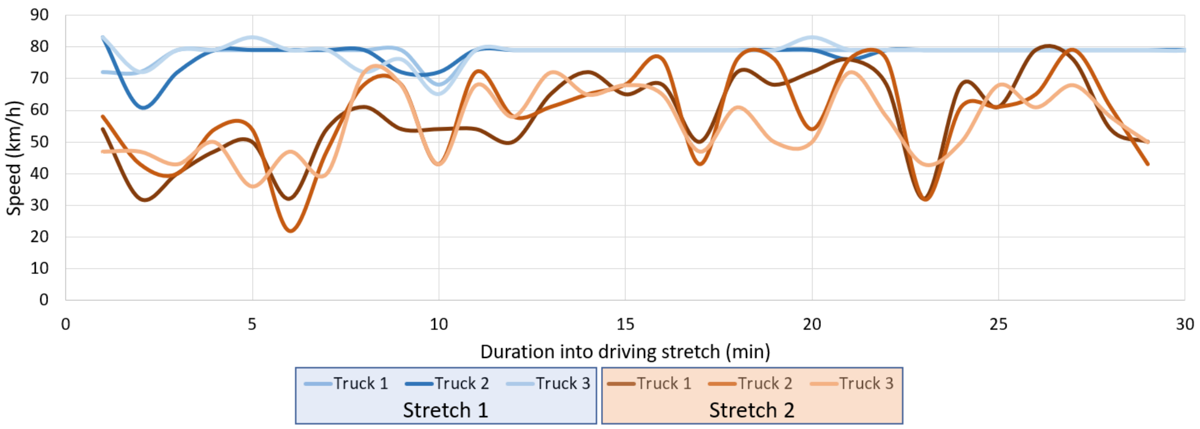


Figure A2: Platoon speeds for sections 1 and 2.

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].

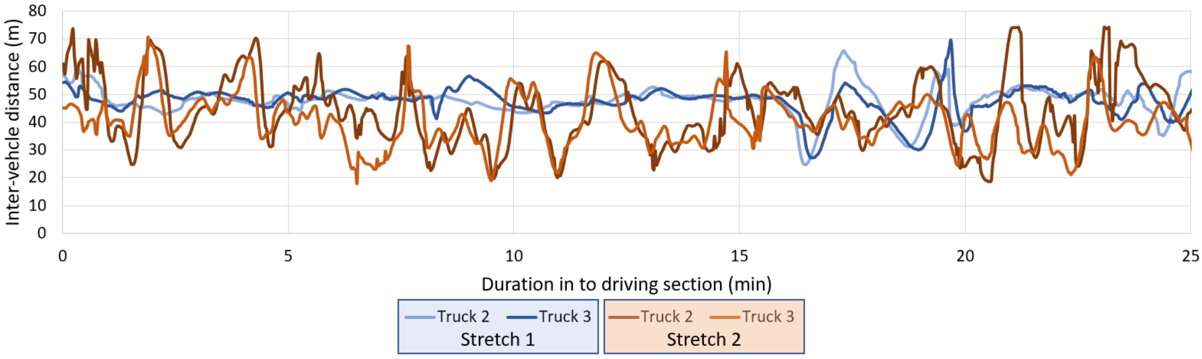


Figure A3: Inter-vehicle distance measurements (1 Hz) from the following trucks during the two excerpts.

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