Fleet Concept of Operations for Automated Driving Systems (ADS): Operational Use Case Documentations and Deployments

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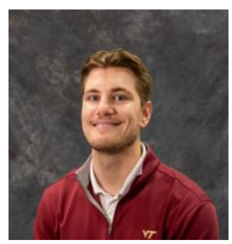

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Abstract

Implementing an Automated Driving System (ADS) within a fleet is a complex undertaking that requires careful planning, analysis, and data collection in defining the domain space and evaluating the impact of automation across organizational levels. The VTTI research team documented and demonstrated safe and efficient integration of ADS-equipped trucks into three realistic use cases: (i) port queueing operations; (ii) cross-country road trips; and (iii) freight integration. These operational use cases represent example equipment and conditions to observe the benefits of ADS-equipped trucks and collect data with live traffic. These three deployments build towards a network of fully deployed ADS trucks integrated into a truck fleet's traditional commercial operations and provide insights into ADS-equipped truck performance in revenue-producing operations. The introduction of automated heavy vehicles has the potential to revolutionize the transportation industry, offering unprecedented opportunities for freight efficiency and road user safety.

Keywords: automated driving systems; freight; trucking

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1. Introduction

Automated Driving Systems (ADS) are set to revolutionize the transportation system. Commercial motor vehicles (CMVs) equipped with ADS offer the potential to improve safety in long-haul trucking by eliminating human limitations such as fatigue, impairment, and distracted driving behavior (Slowik and Sharpe, 2018; Krum, 2024). By decoupling some freight operations from the limitations of driver hours of service (HOS), ADS can improve delivery times, enhance value during driver HOS, and increase the utilization of capital equipment (Fussner, 2022). Additional benefits may be realized that impact the management of limited resources, such as the charging and refueling of electric and green-fuel heavy vehicles, as well as flexibility to schedule operations to reduce congestion and energy demands (Krum, 2024).

The movement of freight is segmented by units such as containers, pallets, and parcels. Once these units arrive at ports they are moved inland on trucks and trains between inland ports, hubs, and distribution centers. The movement of freight on trucks is a highly manual process and one that has been growing in volume and demand in recent years (Wolfe, 2025). Many freight and technology developers are converging to find ways to increase efficiency and optimize delivery through the integration of automation with manual supervision across many use cases (Krum, 2024). However, implementing these systems within a fleet is a complex undertaking that requires careful planning, communication, data collection, and analysis in defining the domain space and evaluating the impact of automation across organizational levels.

To better understand the growing demand for freight movement and the lack of supply of drivers and truck operating hours, three operational use-case deployments on ADS-equipped heavy truck-tractor trailers were conducted to demonstrate the safe and efficient integration of ADS-equipped trucks into existing fleet operations: port queueing operations, cross-country road trips, and internal port operations. Given the tremendous potential safety, efficiency, and productivity benefits of automated trucks, and the fact that 100% of all consumer goods are delivered via trucks, their deployment is expected to benefit all road users and consumers, in addition to those working in the trucking industry.

2. Objective

An objective of the Trucking Fleet Concept of Operations for Automated Driving System-equipped Commercial Motor Vehicles (CONOPS) project was to document how ADS technology can be customized to support fleet operations under specific trucking use case deployments, such as port queuing conditions, over-the-road trips, and fleet integration. During these deployments, the research team observed and documented use case operations, identified key metrics and documented protocols for collecting these variables, and developed public use datasets to provide researchers and policymakers with key data to support the implementation of ADS technology on U.S. roadways.

3. Method

Three operational use cases were deployed to explore, document, and showcase how ADS-equipped trucks can be customized for specific fleet use cases and to collect data on the existing infrastructure on U.S. roadways to support ADS implementation. The operational use cases were port queuing, cross-country trips (similar to over-the-road operations), and internal port operation. The research team evaluated the impacts of ADS technologies by conducting observations and interviews. For the port operation, the approach involved collecting a baseline of the organization before automation and a subsequent analysis following the implementation of automated trucks into operations.

3.1 Port of Oakland Queuing Deployment Method

To explore solutions for reducing wait times at ports and to exhibit the safe implementation of ADS in port queuing operations, the Virginia Tech Transportation Institute (VTTI) research team conducted a series of tests at the Oakland Ports in California to better understand the suitability of this technology in relieving major port congestion points in daily port operations. For four months, the ADS developer, Pronto, developed and tuned their ADS platform to participate in daily port queueing activities at the Oakland ports deployed an automated queuing trial at the Port of Oakland, California. For the ADS-equipped vehicle to be successful at participating in queue operations, Pronto spent most of the testing time tuning the system to be an effective driver under those circumstances. Key modifications to their base algorithms included reducing the transition time between the ADS being stationary and reinitiating motion to keep tighter gaps between vehicles; and improving object detection and tracking algorithms to prevent collisions during aggressive low-speed cut-ins. To showcase the capabilities developed during those months, VTTI and Pronto set up a week of Port Queueing deployments.

3.2 Cross-Country Deployment Method

To showcase the deployment of ADS technology for long-distance hauling from exit to exit, and to gather real-world data for assessing existing road infrastructure to accommodate ADS, the team documented the deployment of cross-country road trips along major freight corridors in the U.S. The initial phase of these cross-country trips aimed to evaluate the ability of the current road infrastructure to support ADS by collecting data on lane marking quality, cellular connectivity, road conditions, and GPS signal strength. Five specific routes were chosen for these trips to gain insight into infrastructure readiness and the performance of ADS under common U.S. driving conditions, which could influence the broader application of ADS in fleet operations. These routes are frequently used by fleets and feature a range of driving challenges, diverse terrains, and varying weather conditions. Table 1 and Figure 1 describe the five routes and duration during the cross-country deployment.

Table 1 – Trip Routes and Duration During the Cross-Country Deployment

Trip Routes	Duration of the Trip
Nationwide Cross-Country Loop	October 25, 2021, to December 1, 2021
California (CA) – Texas (Round trip)	December 14, 2021, to December 21, 2021
Calgary, Canada – CA (One way trip)	January 12, 2022, to February 6, 2022
CA – Florida (Round trip)	February 28, 2022, to March 13, 2022

Trip Routes	Duration of the Trip
CA – Oregon – Washington – Idaho – Montana – Wyoming – Utah – Arizona – Nevada – California	November 12, 2022, to November 17, 2022

Figure 1 – States Travelled in Cross-Country Deployment

A number of trucks equipped with similar ADS capabilities, capable of Level 4 automated driving, were utilized for these cross-country deployments. Although these trucks are automated, safety operators were present to intervene when necessary. The deployments included phases where the ADS was in control and instances where human drivers took over. The primary infrastructure metrics measured included cellular LTE connectivity, lane marking quality, road surface quality, and GPS coverage (Table 2).

Table 2 – Primary Infrastructure Metrics Quantified in the Cross-Country Dataset

Signal Strength	The cellular connectivity was measured by signal strength. The raw signal strength is a value in the range [0, 31]. The signal strength as a percentage is computed as: "percentage_SignalStrength" = "raw_SignalStrength" / 31.
Lane Score	The dataset has lane scores between 0 and 1. The scores indicate the ability to detect lane lines. Here, a score of 1 or close to 1 is the best score, whereas a score of 0 is the worst score.
Road Condition (Smooth or Bumpy)	Road condition was calculated using car state, such as acceleration, yaw, pitch, roll, and speed. The road condition is computed only when vehicle velocity is greater than 40 mph.
GPS Satellites (Counts)	This variable provides the count of the GPS satellites that the ADS was able to detect during the cross-country drives.

The data from these trips, including inertial measurement unit and infrastructure metrics, were recorded in CSV format. Additionally, images were captured at a rate of 25 frames per second using front-facing cameras and stored in JPEG format with unique file names.

3.3 Fleet Integration Deployment Method

To document methods for evaluating fleet integration, the team observed the use of ADS-equipped CMVs in an intermodal heavy truck fleet in Whittier, Alaska. The team investigated both organizational and individual elements to produce a macrocognitive model of human involvement within their tasks and roles. The team conducted a comprehensive review of fleet safety and container lift operator training materials. This was followed by two types of site walk-throughs: a non-active barge visit to observe infrastructure and interview personnel, and a review of recorded footage from an active barge off-load to assess operational patterns. On-site, the team observed live barge operations, including interactions between lifts, trucks, and railcars, while also noting key performance metrics. Video and vehicle data were collected on the ADS-equipped trucks (Figure 2). Following these observations, the team conducted nine semi-structured interviews with various personnel, including truck drivers, forklift operators, and maintenance workers. Additionally, the team observed aerial footage of barge activities to further understand operational dynamics and identify inefficiencies.

Figure 2 – An ADS-equipped truck recording multiple synced videos during barge operations in Whittier, AK. Views include exterior forward over the hood (top-left),

interior cab over driver shoulder (top-right), exterior rear passenger-side (bottom-right), and exterior rear driver-side (bottom-left).

Two controlled demonstrations were observed to provide insight into the process of implementing ADS operations. The first demonstration focused on the truck's automation capabilities, while the second demonstration examined interactions between the ADS truck and lift operators. Researchers observed truck maneuvers, stop points, and communication strategies, both from the ground and by riding with lift operators. Data was collected through interviews, walk-throughs, and demonstrations, modified to fit the unique conditions of ADS integration. Interviews were conducted with nine participants, including safety drivers, engineers, and forklift operators, focusing on how ADS-equipped trucks would function in the yard. The team also received detailed walk-throughs of the ADS equipment and procedures from the safety driver, highlighting the steps involved in inspecting and operating automated trucks.

4. Results

4.1 Port of Oakland Queueing Deployment

Pronto conducted a series of tests during the week-long Port Queuing deployment use case at the Oakland Ports in California. VTTI documented this deployment to better understand the suitability of this technology in relieving major port congestion points in daily port operations. The port queuing deployment documented scenarios where ADSs and drivers interact during different phases of port activities. These included (1) a driver manually navigating to the terminal queue, (2) the activation of ADS allowing the truck to join the queue in automated mode until reaching the terminal gate, and (3) the driver taking back control from ADS to manually enter the terminal and move within the port to the loading area. The results from the port-queuing deployment observation illustrate the challenges of initial integration and the data required to evaluate whether an integration is successful.

During the week-long Port Queuing deployment, an ADS-equipped truck successfully delivered at least one container daily over five days. The Pronto team gathered 181 minutes of data from these operations, including vehicle state information stored in CSV files. Additionally, video footage was captured from the front-facing camera during these queuing operations, saved in .jpeg format with distinct filenames for each frame (Figure 3).

Figure 3 – Video Captured During Port Queuing Deployment

Upon initial integration, the ADS vehicle was proficient at traversing the routes of different queues, but it was unable to handle the speed and aggressive driving of other drivers. For example, as the queues progressed, any significant gap between the ADS-equipped vehicle and a leading truck would be a target for another driver cutting the line. In addition, if the ADS-equipped vehicle was driving too slowly or pausing when the queue started moving, it would be a target of aggressive honking and yelling by other drivers. From these observations, the Pronto team modified their base algorithms to account for the context of port-queueing more effectively. Key adjustments included reducing transition time between the ADS being stationary and reinitiating motion when the queue resumed, improving the tuning of the ADS's adaptive cruise control to keep tighter gaps between leading vehicles; and improving object detection algorithms to prevent collisions during aggressive, low-speed cut-ins.

To test the effectiveness of the newly modified ADS-equipped vehicle, the VTTI team used cameras and vehicle outputs to understand how the vehicle performed in this environment. The measures include braking, drive state, throttle, gear, steering angle, vehicle speed, acceleration, and position metrics like latitude, longitude, pitch, yaw, and roll. These metrics were collected during the week of evaluation where the Pronto ADS vehicle delivered at least one container a day for five days. The data was collected and published in the VTTI CONOPS Dataverse (Krum, 2024).

4.2 Cross-Country Deployment

To properly monitor and support the driver of an ADS-equipped vehicle, the infrastructure must be able to support these operations. Under various roadway conditions, weather conditions, and times of the day, the communication signal between the truck and support operations can become weakened or interrupted. VTTI documented the cross-country road trip deployments to better understand key data metrics, infrastructure requirements, and collection methods required for the ADS-equipped vehicle to successfully operate and provide ADS-developers information about successful deployment.

Data obtained from these cross-country deployments were used to develop a road readiness rating system for ADS technology. The rating system combined data from FHWA's Highway Performance Monitoring System (HPMS) database with data collected from the ADS-equipped trucks, including the ADS-detected real-time lane marking quality, cellular connectivity (i.e., signal strength), GPS connectivity (i.e., count of GPS), and road condition (i.e., bumpiness/smoothness). The assessment used the ADS data to provide a detailed evaluation of the lane marking quality (0 to 10 scale) on all the roadway segments traversed by the truck. Cellular strength (using percentages) and GPS counts on these segments were assessed, and each of these metrics was geolocated on a geographic information system (GIS)-based map to visualize the readiness of the roadways on these cross-country routes to support ADS technology.

The results of this deployment are the publicly available data in the VTTI CONOPS Dataverse covering approximately 15,400 miles of travel on Interstate highways. This includes travel on approximately 10,790 centerline-miles of Interstate highways, 81% of which were driven in one direction of travel only and 19% of which were driven in both directions of travel. Some Interstate highways were driven more than once in the direction of travel. Because these drives were made at different times (typically on different trips), they provide separate observations, and both trips over a given direction of travel were used as separate observations in the analysis. The 10,790 centerline-miles of Interstate highways traveled constitute approximately 23% of Interstate freeways in the United States. The routes covered complex driving conditions, various terrains, times of day, and weather conditions.

4.3 Fleet Integration Deployment

Organizational elements were thoroughly defined as they exist at an operational level to better understand the implications of introducing ADS into an intermodal fleet operating heavy trucks for repetitive driving actions in a private yard. The research team accomplished this by collecting relevant observational and interview data and using those data to perform various task, risk, and organizational systems analyses. The approach established a baseline evaluation of the organization for future use in identifying the impacts of incorporating automated vehicles.

To fully grasp the interaction between personnel, equipment, and processes during a barge off-load operation, a clear understanding of the overall structure and flow is essential. The operational objective is to transfer full containers from the barge to railcars for outbound shipment, supported by several interconnected subprocesses. Coordination between the freight operator (FO) crew and the railroad team is critical, as railcar operations must align with the barge's arrival. The off-load begins with removing empty containers and freight from inbound railcars, which creates space for the incoming freight from the barge. The barge is then secured to the dock, allowing the rail workers to remove railcars from the barge before the FO crew can begin freight off-loading. This process is reflected in Figure 4.

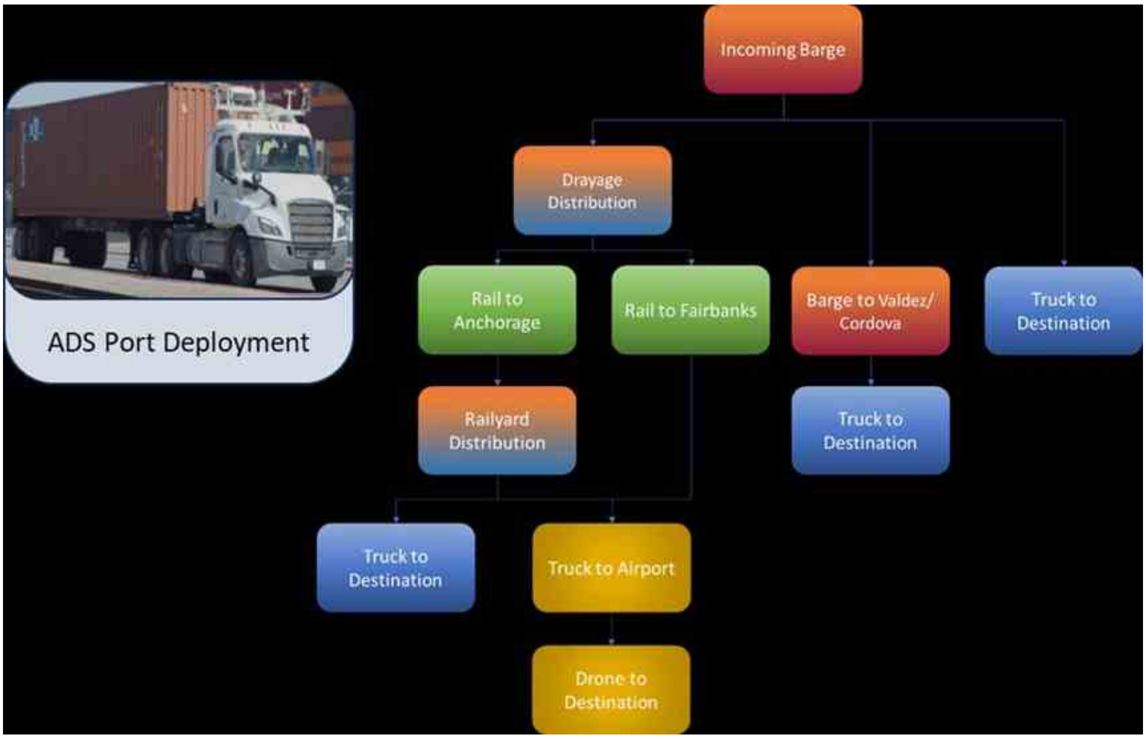

Figure 4 – Flowchart of Cargo at the Port of Whittier and the ADS-impacted Operation

A structured process ensures efficiency and safety, starting with a crew safety briefing while railcars are cleared (Figure 5). Once the railcars are removed, the forklift operator secures ramps to give lifts access to the barge. Freight is then unloaded and distributed across the yard based on its destination, whether for rail, truck, or temporary storage. After off-loading, the empty containers and outbound shipments are reloaded onto the barge for their return to Seattle. Understanding this sequence is vital for identifying the critical interactions and dependencies that drive operational efficiency and safety. This knowledge supports better process improvements, highlighting where inefficiencies may arise and ensuring alignment between equipment, personnel, and logistical demands.

Figure 5 – Barge with Ramp Connections Labeled and Winter Operations at Whittier

To map the operational workflow, the research team analyzed findings using principles from macrocognition and Human Reliability Analysis (HRA). The macrocognitive perspective emphasizes understanding human processing in real-world settings by breaking it into five key components: detecting, sensemaking, decision-making, action, and coordination. These elements are interactive but can function independently, providing insight into how personnel respond and adapt to changing conditions during barge off-loads. HRA further enriched the analysis by incorporating Performance Influencing Factors (PIFs), which predict potential errors or failures based on factors like task complexity, time pressure, and stress. By integrating both perspectives, the team gained a deeper understanding of how human cognition and external conditions impact the efficiency and safety of the barge off-load process. This effort produced a series of risks among the FO crew, portrayed in Table 3.

Table 3 – Various Risk Characteristics that Could Impact a Worker Across the Five Components of Human Processing

Risks to Detection	Risks to Sensemaking	Risks to Decision-making	Risks to Action	Risks to Coordination
Ambient Noise	Attention	Expectation	Attention	Attention
Attention	Experience	Experience	Experience	Ambient Noise
Experience	Failed Detection	Fatigue	Fatigue	Equipment Failure
Fatigue	Fatigue	HMI	Human-Machine Interface	Experience
Low Visibility	Human-Machine Interface (HMI)	Incorrect Sensemaking	Road Conditions	Fatigue
Object Salience	Incorrect Detection	Personality	Stress	Stress
Occlusions	Motivation	Safety Culture	Training	Low Visibility
Stress	Stress	Stress	Temperature	Role Awareness
Workload	Training	Training	Vibration	Safety Culture
	Trust	Workload	Wind	Training
	Workload		Weather	Workload

Building on the initial analysis of port operations with manual trucks, the research team used similar tools to examine the impact of ADS on port activities.

From a sociotechnical perspective, ADS complexity increases as operational control decreases. In a controlled yard environment, factors such as route repetitiveness, traffic, and public access impact how the ADS operates. Core ADS systems, including perception, localization, control, and decision-making, must work seamlessly, supported by secondary systems like cybersecurity, energy management, and validation checks.

4.4 Dataverse

A key result and output of this project was the development of an open-source data repository, the VTTI CONOPS Dataverse, to store and manage data collected from the deployments. This publicly available collection serves as a centralized interface for researchers and stakeholders to access non-proprietary data generated throughout the study to answer their own research questions. The repository encompasses a wide range of data collected throughout the project, including:

- **Operational Data from ADS Trucks**: This includes video footage, kinematic data, radar outputs, GPS information, and other sensor-based datasets.

- **Driver Monitoring Data**: Collected during deployments involving ADS, these datasets capture driver behavior under three distinct use cases: port queuing, cross-country trips, and port integration.
- **Public Perception Surveys**: Responses from outreach events and roadshows that gauge public attitudes toward and acceptance of ADS technologies.

All datasets are published on the VTTI CONOPS Dataverse with permanent digital object identifier (DOI) citations, ensuring accessibility and traceability. As the datasets do not contain proprietary, confidential, or personally identifiable information, there are no concerns regarding privacy, ethics, or confidentiality. The data is systematically organized based on deployment use cases.

For the Port Queuing use case, Pronto's logging system recorded data in one-minute increments, resulting in structured CSV files and corresponding images. The data is stored in two dedicated folders: one containing trip-organized CSV files with subfolders named by specific data types (e.g., carState, IMU, GPS RTK, frames), and another containing JPEG images, also organized by trip. Similarly, the Cross-Country use case followed the same logging methodology. Five cross-country trips were conducted, including routes such as Nationwide Loop, San Francisco–Texas–San Francisco, and San Francisco–Calgary–San Francisco. The data was uploaded to the Dataverse and structured by state and trip name, with further subfolders categorizing CSV files by collection date and images by timestamp (day-hour-minute). Lastly, the Fleet Integration dataset mirrors the structure of the Port Queuing dataset, with vehicle state information stored in CSV format and front-facing images captured during deployment. This consistent and structured approach to data organization ensures efficient accessibility and usability for researchers, policymakers, and industry stakeholders.

5. Discussion

These results from CONOPS are valuable for fleet managers, policymakers, ADS developers and the public, offering insights into the challenges and benefits of implementing ADS in a manner that is safe and efficient for all road users. ADS-equipped trucks were deployed in three different use cases, port queuing, over-the-road, and in a private port; best practices and applications, and lessons learned during the deployments are discussed.

The problem of increasing wait times at U.S. ports and other critical shipping hubs is escalating. Over the last 10 years, the size of container ships has significantly expanded, with the largest vessels now capable of transporting more than 20,000 twenty-foot containers, up from around 8,000. Despite these advancements, port facilities and technologies, such as truck reservation systems, have struggled to keep up with the volume of shipping containers. Consequently, the waiting times for trucks to load and unload these containers have substantially increased, sometimes exceeding 6 hours (Figure 6). These delays significantly impact the productivity of drivers and carriers, as they reduce the number of hours a driver can operate within regulatory limits. Typically, commercial drivers are permitted 11 hours of driving within a 14-hour work period. With most being paid per mile, extended wait times can drastically cut into their earnings.

Figure 6 – Truck Queuing at US Ports

ADS could offer a solution by enabling trucks to operate in “Level 4” mode while in a queue. With ADS, drivers could potentially go off duty and rest, either in a sleeper berth or by using facilities at the port or nearby motels. This rest period would not count against the driver’s hours of service (HOS), thus enhancing overall productivity, increasing the carrier’s profitability (by covering more distance daily), and improving safety as drivers would be better rested and less stressed by time constraints. Additionally, for local deliveries, this technology could transform port operations. A driver might navigate through city traffic to the port queue manually, then switch the vehicle to automated mode—thus reserving precious HOS—and pick up another loaded ADS-equipped vehicle later. This would effectively increase the number of trips a driver could complete in a day.

The port queuing use case sought to address the problem of lost utilization of labor due to the driver waiting for hours in line at a port and lost utilization of the truck equipment later when the driver’s hours of service run out. This deployment of an ADS-equipped truck highlighted lessons learned, including the need for humans to be onboard to operate the truck during some parts of trips, such as when nearing the port gate. The need for ADS to operate at low speeds in high freight traffic volumes on the side of public roads and the opportunity for low-latency communication systems to be made available to support ADS vehicle operations were also evident with this deployment.

Long-haul drivers often endure fatigue due to extended periods behind the wheel, including interstate travel and varying roads, weather, and lighting conditions. ADS offers a solution whereby the system collaborates with human drivers, taking control of the vehicle when the driver is fatigued. This allows a non-team driver to rest without sitting at a truck stop operating within the ADS’s operational design domain. This ideal application not only lightens the driver’s workload but also enhances safety for all road users and optimizes fleet resources by facilitating longer trips with ADS support. The over-the-road use case collected data from an ADS-equipped truck during long cross-country trips. This use case could be representative of an early deployment opportunity for Level 4 ADS-equipped trucks to operate among nationwide hubs. The purpose of these trips for the developer was primarily testing. It also provided an opportunity to cooperate and use the ADS-equipped truck and support vehicles to collect roadway data that may be necessary for ADS operating communication, command, and control. A best practice that emerged from this deployment was to improve low-rating roadways to adequately support new and emerging technologies such as ADS, State DOTs can start with improving roadway maintenance operations, such as repainting lane markings, clearly identifying shoulders, and improving pavement condition. Further, the efficiency and coverage of communication technologies such as GPS and cellular should be assessed for various roadways, especially those serving fleets.

The private port fleet integration use case addressed the need to operate trucks on high-demand schedules that occur sporadically for one to two 24-hour periods a week to support barge and rail container movement. This deployment of ADS-equipped trucks highlighted an ideal application and integration opportunity between port workers and ADS-equipped trucks. The deployment illustrated the development that is needed across the entire organization to balance automation performance with human expectations and challenging site structural and environmental conditions. A best practice and lesson learned during this deployment was importance of studying previous metrics prior to implementation and considering the implications of implementation throughout the entire operational system in order to achieve an effective analysis of autonomous technology integration.

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