Cooperative Driving Automation: Research into Automated Port Operations and Automated Commercial Motor Vehicle Operations

Final Report: Proof-of-Concept Port Drayage Use Case

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16. Abstract

The objective of this task is to demonstrate CDA technology with loading and unloading of containers to and from chassis, inspection point passage, gate passage, and short-haul drayage. The required software development of the port drayage plugin and web UI was performed, the plugin was tested at ATEF and SunTrax, and the complete use case was demonstrated at SunTrax, in Auburndale, Florida. This use case proved the benefits that could be realized through application of CDA in the U.S. ports. While port drayage is one process that involves many challenges related to congestion, air quality, and potentially safety, the use case points out many areas of benefits. First, the communication involved in CDA between the automated truck and the infrastructure is key to support the complex logistics within the U.S. ports to guide drives/operators on when/where they should move the trucks. Second, the path planning required required for the movement of the automated truck is another crucial element to enable optimal and safe movement of the drayage trucks within the port and between the port and staging area. Third, through communication and automation, the trucks can be alert and responsive to changing conditions at the ports, hence congestion could be managed and all the associated impacts (e.g. emissions) could be addressed.

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SI* (MODERN METRIC) CONVERSION FACTORS

Approximate Conversions to SI Units

Symbol	When You Know	Multiply By	To Find	Symbol
		Length		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		Area		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yards	0.836	square meters	m^2
ac	Acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		Volume (volumes greater than 1,000L shall be shown in m^3)		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		Mass		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2,000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		Temperature (exact degrees)		
°F	Fahrenheit	5(F-32)/9 or (F-32)/1.8	Celsius	°C
		Illumination		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		Force and Pressure or Stress		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

Approximate Conversions from SI Units

Symbol	When You Know	Multiply By	To Find	Symbol
		Length		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		Area		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
Ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		Volume		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		Mass		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2,000 lb)	T
		Temperature (exact degrees)		
°C	Celsius	1.8c+32	Fahrenheit	°F
		Illumination		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		Force and Pressure or Stress		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

* SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380. (Revised March 2003, Section 508-accessible version September 2009.)

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List of Acronyms, Abbreviations, and Symbols

Acronym	Definition
ADS	automated driving system
APG	Aberdeen Proving Ground
ATC	Aberdeen Test Center
ATCMTD	advanced transportation and congestion management technologies deployment
ATEF	Automotive Technology Evaluation Facility
CAV	connected and automated vehicle
CCTV	closed-circuit television
CHE	container handling equipment
CMV	commercial motor vehicle
CAVe	Connected and Automated Vehicle education
ConOps	concept of operations
DSRC	dedicated short-range communication
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
HRDO	Office of Operations Research and Development
ITS	intelligent transportation system
ITS MARAD	Intelligent Transportation Systems Maritime Administration
ITS–JPO	Intelligent Transportation Systems-Joint Program Office
JPO	Joint Program Office

LA	Los Angeles
MARAD	Maritime Administration
ODD	operational design domain
OTR	over the road
R&D	research and development
RSU	roadside unit
SAE	Society of Automotive Engineers
STOL	Saxton Transportation Operations Laboratory
TAS	truck appointment system
TFHRC	Turner-Fairbank Highway Research Center
TOSCO	Traffic optimization for signal corridors
USDOT	U.S. Department of Transportation
V2X	vehicle-to-everything

Chapter 1. Introduction

Background

The Federal Highway Administration (FHWA) Office of Safety and Operations Research and Development (HRSO) performs transportation operations and research and development (R&D) at the Saxton Transportation Operations Laboratory (STOL), established at the Turner-Fairbank Highway Research Center (TFHRC). The government has a number of development projects underway that are using Agile Development practices to create open-source software with robust Communities of Practice. Each of these projects support different parts of an overall Intelligent Transportation Systems (ITS) deployment architecture and are managed separately, with individual development teams. In support of common goals, the Maritime Administration (MARAD) and the Federal Motor Carrier Safety Administration (FMCSA) have partnered with FHWA and STOL to explore the application of cooperative driving automation (CDA) to CMV operations. Four CMVs are being equipped with automation technologies, including CARMA, to enable a SAE Level 2-3 operation, furthering the research opportunities and capabilities available to FMCSA, MARAD, and the government.

MARAD, in conjunction with Intelligent Transportation Systems – Joint Program Office (ITS-JPO) research programs, seeks to increase cargo capacity and reliability of freight moving through ports. MARAD is engaged in a multi-year research program that seeks to achieve two primary goals:

1) To identify opportunities to conduct research that addresses critical freight movement and ITS infrastructure gaps; and
2) To identify opportunities for pilot projects and programs to be deployed, including technology transfer.

The ITS MARAD program is a joint USDOT initiative, co-led by the ITS-JPO and MARAD with modal participation from FHWA and FMCSA. The goal of the program is to use ITS to improve the performance of maritime ports and terminals, along with the larger freight network. The program completed the Business Case Assessment project in October 2017. The team conducted outreach with stakeholders and developed a portfolio of business case assessments for four candidate ITS solutions. The program is continuing to work on identifying a portfolio of projects that agencies, including port authorities, can implement through Advanced Transportation and Congestion Management Technologies Deployment (ATCMTD) and other grants to address port and freight-related challenges. The program is working toward a long-term outcome of field operational testing of the technology solutions, one of which may include automated truck queuing at ports. In May 2019, the program completed the ITS MARAD Truck Staging Study, including an economic feasibility study of several port & truck queuing solutions. The program is working with relevant maritime stakeholders on ensuring effective technology transfer activities of the completed products and tools,and is developing plans for future evaluation activities.

The Cooperative Driving Automation Port Drayage Development and Testing initiative is a demonstration of CDA in a port environment in a multi-year phased project to increase efficiencies, increase safety, and decrease emissions. The project objective is to further the technology implementation in our nation's ports to accelerate the adoption of the technologies available, and to show a positive cost/benefit of automated truck movement in queues at ports and staging areas or warehouses. The project demonstrates CDA technology applications with loading and unloading of containers to and from chassis, and short-haul drayage between a mock staging area and a mock container port terminal. This project focuses on enhancing CARMA Platform and CARMA Streets℠ through agile software development to support other CDA use cases.

Goal

The purpose of this task is to develop a proof-of-concept application in support of loading and unloading shipping containers, using a CARMA-equipped CMV. This application demonstrates the use of CDA to interact with the port infrastructure to increase freight movement at ports. Federal agencies coordinating on the project include ITS-JPO, MARAD, FHWA, and FMCSA.

The key objectives of this task are to:

- Demonstrate CDA technology applications with loading and unloading of containers to and from chassis, inspection point passage, gate passage, and short-haul drayage.
- Build upon and extend the research from Prototype II (693JJ318F000225) that developed CARMA Platform and CARMA Streets.
- Focus on enhancing CARMA Platform and CARMA Streets through agile software development to supporting other CDA use cases.
- Test and demonstrate the proof-of-concept port drayage use case in test tracks.

This report provides a detailed overview of the research effort, results, and lessons learned in this proof-of-concept port drayage development and demonstration task.

Document Contents

Chapter 2 defines the issues, challenges, and potential for automation at ports.

Chapter 3 describes the integration testing of the port drayage use case.

Chapter 4 describes the verification and validation testing of the port drayage use case.

Chapter 5 describes how the proof-of-concept port drayage use case was demonstrated and discusses in detail the various actions and steps involved.

Chapter 6 discusses the data collection and analysis for the port drayage plugin and functionalities.

Chapter 7 summarizes the work and provides the project conclusion.

Chapter 2. Issues, Challenges, and Potential for Automation

Short-Haul Drayage Process

Drayage is an important part of maritime supply chains, and often accounts for a disproportionately high percentage of overall transportation costs and a large proportion of truck arrivals at container terminals. A general definition of drayage used in the shipping industry and logistics is “drayage is the transport of goods over a short distance, often as part of a longer overall move and is typically completed in a single work shift [1]. This general definition has been refined by the project team to read “Port drayage is the pick-up or delivery of containers by truck to a container terminal in which both the trip origin and destination are in the same geographic region.” As such, all short-distance truck transport of containers to or from the port—no matter if it is an import, export, or transshipment container—is considered port drayage.

Automating Port Drayage Process

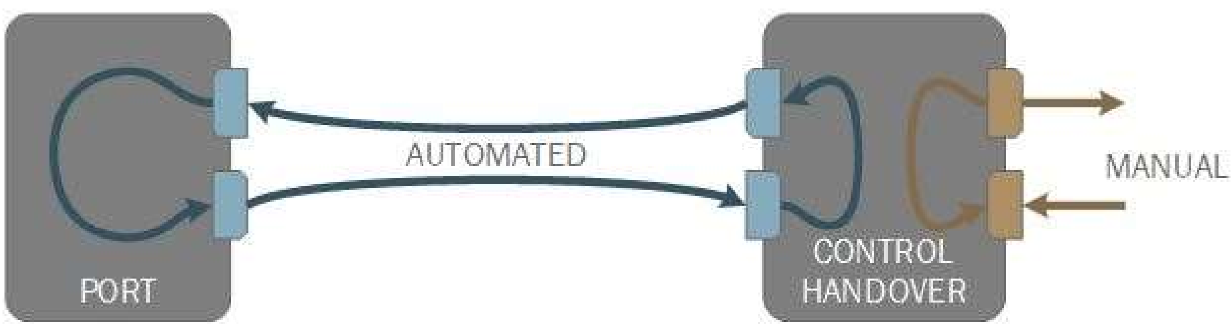
The move toward automation of container terminal processes is motivated by the potential for improved reliability, efficiency, consistency, predictability, and worker safety, as well as reduced cost of operations. Reduced environmental impacts may also be a guiding factor particularly with automation that could alleviate truck congestion.

To enable automation of the truck port drayage process, this project addresses the software development and proof-of-concept testing using an automated CMV. The CMV demonstrated loading and unloading of containers to and from chassis, inspection point passage, gate passage, and short-haul drayage. The goal is to demonstrate a proof-of-concept of applications to show how automation might be applied to drayage operations to address the aforementioned issues and improve operational efficiency at container terminals.

System Overview

This study focuses on improving the efficiency of container terminal short-haul drayage using CDA. Container terminals are complex, and they are varied to suit the unique needs of each port. While the primary goal of all ports, in general, is similar—to move goods—factors like location, size, and demand drive key differences in individual ports. For instance, on a wheeled facility, containers are loaded onto a chassis by the terminal operators prior to pick up, whereas in a stacked facility, containers are stored in stacks of containers and are loaded onto the chassis as part of the pick-up process. Wheeled facilities have containers on chassis, which typically requires larger space, so they are more feasible at terminals with lower volumes. Some facilities stack most of their containers but maintain a wheeled section for specific customers. This is a key difference that would affect the ability to implement improvements to ports, broadly.

The system considered in this concept uses a scenario introduced in the MARAD Truck Staging Study involving an off-site location where automated and manned trucks exchanged their shipments of containers. From a technological standpoint, the staging area in the MARAD study represents a point in which control of the vehicle transporting the container shifts between manual and automation (control handover point). The use of a control handover point allows the project team to focus the project on the ability of CAVs to operate on container terminals including entry and departure from the terminals, rather than studying their performance over an extensive highway network. While it would be difficult to create a business case to support creation of dedicated control handover point, most medium and large size ports already contain rail intermodal terminals, trucking depots for over the road (OTR) trucking firms, and commercially operated trucks stops that are located a short distance from their container terminals that can serve the purpose of a control handover point [2]. While there are numerous options that can serve as control handover points, rail intermodal terminals probably already have fairly advanced computerized yard management systems that could be configured to interact with other IT systems and the drayage operations to the container terminals is probably already well established [3]. The other options mentioned could be used if a computerized yard management systems were supplied. In this scenario, containers that are being drayed from the control handover point by autonomous trucks will be loaded onto trucks with chassis designed to transport containers. The CAV will interface with the container terminal's truck appointment system (TAS) to obtain a gate reservation time. The truck will then transit public roads to the container terminal. The trucks will proceed to the terminal gates, waiting in queue if necessary. At the gate, the truck will stop for a security inspection, conducted by terminal personnel, to ensure that no unauthorized personnel are in the truck or container. This inspection may be conducted remotely by terminal security personnel through the use of CCTV installed at the gate; however, if the container is unsealed [4] and is listed as an empty, someone may be required to open the empty container for inspection by CCTV or a security personnel. The CAV will also provide the documents necessary electronically to the terminal's central system. The CAV will receive the location within the terminal where the container will be lifted off the chassis along with routing and traffic information (other trucks as well as mobile yard equipment operating within the terminal). The flow of automated CMVs between a staging area and the port terminal is illustrated in Figure 1.



Source: FHWA, 2021

Figure 1. Diagram. Flow of traffic between port and staging area in the proposed concept

To translate this concept into a practical demonstration, several assumptions were made:

- Since the CAVs involved are not capable of hitching or unhitching to a chassis, wheel-based container terminals were excluded. On stacked facilities, the container handling equipment is used to load/unload containers onto or off chassis already hitched to a truck. Only stacked container terminal are considered in the study.

- The control handover point should be located within 10 miles of the container terminal. This is because existing automated trucks only cover a limited operational design domain (ODD), and limiting the distance limits the required ODDs. Also, operation of the automated trucks in mixed traffic is considered since having a dedicated lane for an automated truck is not feasible.

Current Challenges

The primary motivation for the proposed concept is to reduce truck congestion on container terminal access roads, gates and within the terminal and to reduce drayage delays within terminals. Congestion-related delays are a main cause of lost productivity of drayage truck drivers. In addition to lost productivity, the congestion causes several externalities, such as environmental degradation and increases in shipment costs.

While the container trade in the U.S. is consolidating into fewer ports, the size of the containerships themselves has increased greatly. This in turn has resulted in larger surges in container-handling operations, hence, surges in truck traffic. Unfortunately, container terminals are located in major population centers where increasing their sizes is not an option due to the limited space. Since truck traffic is tied to container movements into and out of port facilities, a persistent recurring congestion issue is resulting at container terminals, leading to significant increases in turn times (which includes the entire duration of time for a truck driver to start a trip to a terminal, wait in queue at the terminal gate, conduct the transaction within the terminal, and deliver the cargo to the customer).

Several approaches to address inefficiencies leading to high turn times have been studied and implemented. ITS technology solutions were studied in an internal state-of-the-practice review in phase 1 of the ITS MARAD program. Many solutions identified in that study are aimed at reducing the barrier between container terminals and the drayage trucking industry through improved transparency and visibility of cargo data. One viable solution is the adoption of an efficient TAS. However, there are several barriers to widespread adoption of TAS in U.S. ports—the primary barrier being acceptance by truck drivers. Furthermore, TAS and comparable approaches are likely only effective in addressing delays from predictable causes such as recurring congestion. Thus, delays related to specific incidents could still lead to truck backups and congestion inside and outside of the terminal, even if an efficient TAS is widely accepted by drivers at such terminal.

Unfortunately, risks of severe delays due to non-recurring truck congestion could be significantly high due to the many ends where an incident could start at a terminal. Example incidents include crane incidents, rain and flood damage, straddle overturns, empty handlers, communication errors, collision of ships, stack collisions with yard cranes, fire, theft, poor handling of cargo, handling and pulling of a wrong container, shift changes for terminal staff, lane blockages, computer system breakdowns, and poor chassis condition. Such incidents can lead to disruptions in smooth or planned container terminal operations and have a cascading effect on overall container terminal efficiency, including affecting turn times for trucks. Furthermore, the unpredictability of these incidents can make them hard to manage and mitigate.

System Benefits

Regarding benefits that container terminals would realize through the ground-based use case, the use of automated CMVs for container drayage to and from container terminals has the potential to reduce congestion in the terminals. This will in turn reduce truck queueing times at the terminal's gates and congestion on the approach roads caused by the trucks waiting to enter the terminal. Reduction in congestion will reduce truck turn times, emissions from idling trucks, and will improve the throughput capability of container terminals. Realizing this potential will require that the automated trucks communicate with the mobile container handling equipment (i.e. straddle carriers, stackers, and forklifts) and other trucks in the terminal either directly or through a yard management system operated by the terminal operators. The automation functionality will enable the drayage truck to select the optimum route to the designated container drop-off or pick-up location. On average, each container in a stacked container terminal is required to be moved three times by mobile container handling equipment before it is loaded onto a truck, so the mobile equipment on the terminal is constantly in motion. The automated truck being fed information from the other vehicles/equipment on the terminal will be able to anticipate when driving lanes in the container storage areas will be blocked by other trucks or mobile equipment and will be able to select an alternative route. This will reduce congestion on the terminal. Additionally, having both the truck and the container handling equipment aware of each other's movement and intentions will reduce the potential of collisions thereby improving worker safety in the terminal and potentially minimizing one risk area of non-recurring congestion.

Chapter 3. Integration Testing

Testing Location

The integration and preliminary verification testing of the port drayage proof-of-concept use case was performed at the Aberdeen Test Center (ATC), which is an Army facility on Aberdeen Proving Ground (APG), located in Aberdeen, Maryland, about 75 miles from TFHRC, as shown in Figure 2. The Automotive Technology Evaluation Facility (ATEF) at ATC contains a 4.7-mile, two-lane, paved test track with three intersections and several wide sections of pavement to support various test activities. The facility provides numerous services, such as data acquisition and processing, qualified drivers, test administration, and maintenance staff.

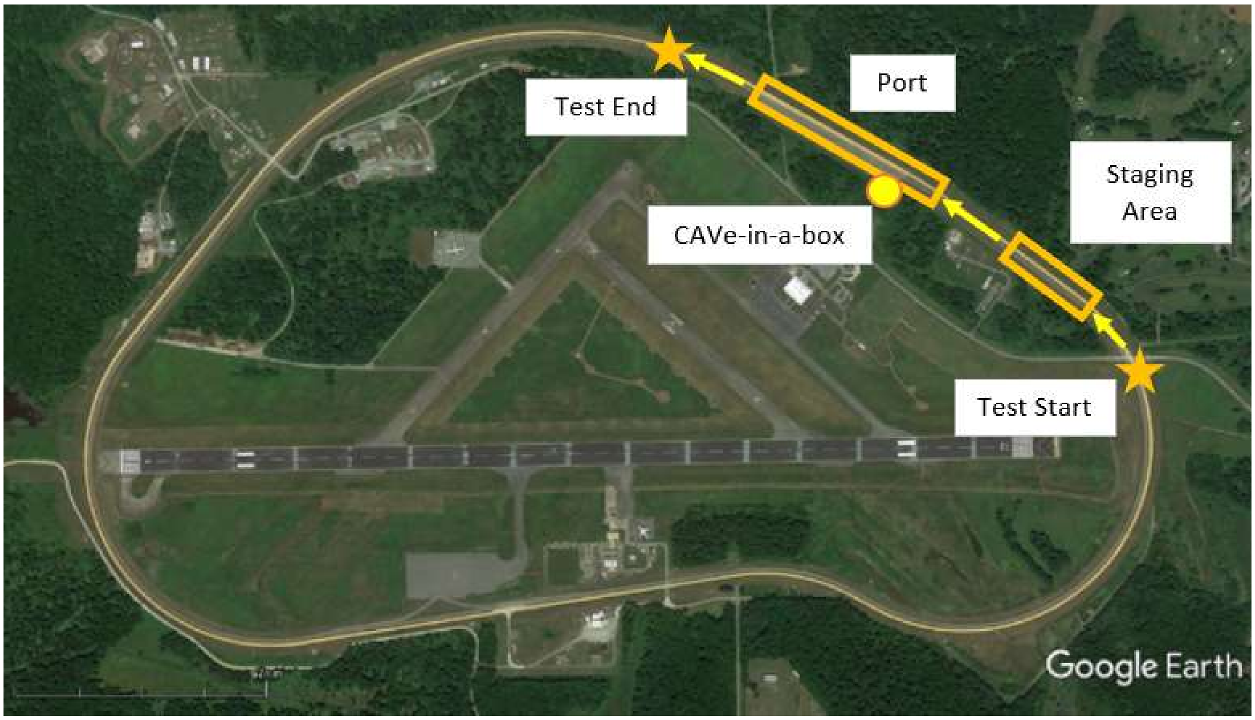
Source: Google Earth, 2021

Figure 2. Aerial view of ATEF at ATC

ATEF was primarily used to test and further develop the CARMA Platform plugins necessary for the port drayage application. Additionally, testing at ATEF focused on integration and further development of the necessary CARMA Streets plugins to enable communication between an automated CMV and a vehicle-to-everything (V2X) Hub that was used to emulate the port infrastructure.

Testing Set Up

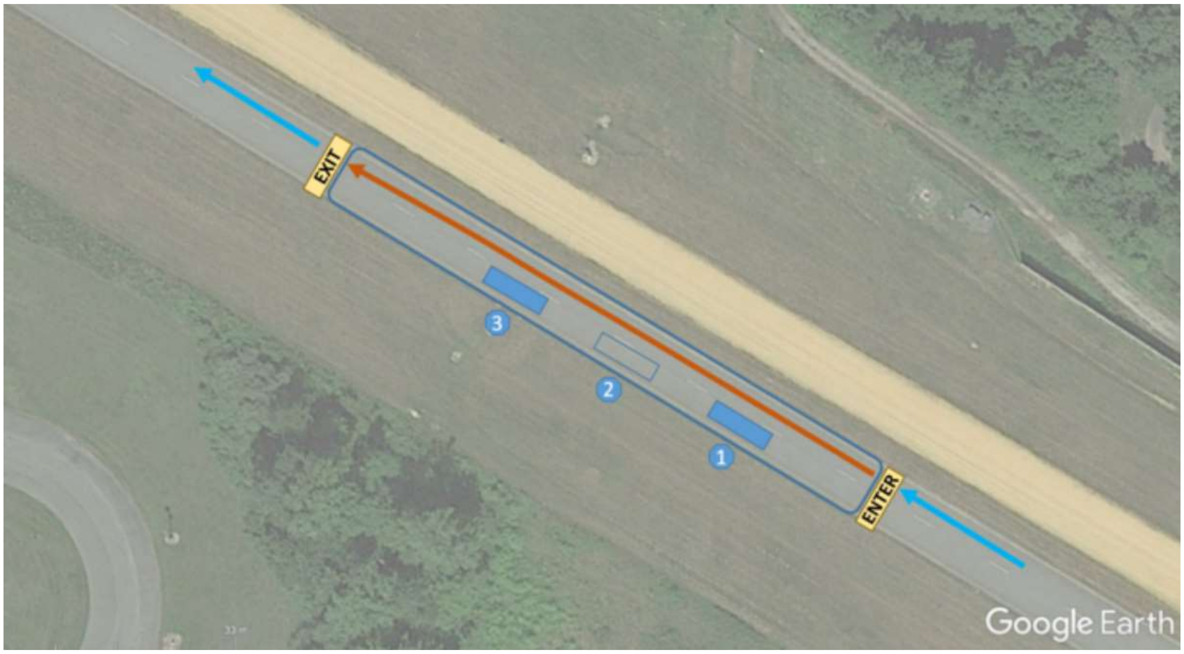
To complete integration testing, a straightaway section of the ATEF track was configured as a mock port and staging area, as shown in Figure 3. A Connected and Automated Vehicle education (CAVe)-in-a-box, with V2X Hub and a roadside unit (RSU), was used to represent the infrastructure component of the test. At this test location, the RSU communication range covered both the port and staging area, so only one unit was used.



Source: Google Earth, 2021

Figure 3. Testing route of ATEF at ATC

Figure **4** and Figure 5 below display the mock staging area and mock port area in more detail.



Source: Google Earth, 2021

Figure 4. Layout of mock staging area at ATEF. Points 1, 2, and 3 are potential cargo pickup locations for the CMV

Source: Google Earth, 2021

Figure 5. Layout of mock port area at ATEF. Point 1 is a cargo dropoff location, points 2 and 3 are potential cargo pickup locations, point 4 is a port checkpoint, and point 5 is a port holding area

Integration Testing

After identifying the segment of the ATEF track that would be used to test the full port drayage proof-of-concept use case, nine destination points (defined by latitude and longitude coordinates) were selected along the track segment and loaded into the port drayage actions database utilized by the V2X Hub instance. The nine required destination points for the use case included the following: Staging Area Entrance, Staging Area Pickup, Staging Area Exit, Port Entrance, Port Dropoff, Port Pickup, Port Checkpoint, Port Holding Area, and Port Exit. These locations, along with the route paths followed by the CARMA system, are displayed in Figure **4** and Figure 5. Once the destination points were loaded into the port drayage actions database, utilized by the V2X Hub instance running on the CAVe-in-a-box, it was possible to conduct the integration test procedure for the use case.

A high-level overview of the integration test procedure steps for the initial portion of the use case are provided below:

1. With the truck positioned at the “Test Start” location displayed in Figure 3 (approximately 100 meters from the Staging Area Entrance), the test engineer manually selects the first route to the Staging Area Entrance on the in-vehicle CARMA Web UI and provides user input to engage the CARMA system.
2. After the truck comes to a complete stop at the Staging Area Entrance, the test engineer provides user input on the CARMA Web UI to acknowledge that the truck has completed its route, and the CARMA system automatically broadcasts the CMV’s arrival message to V2X Hub.
3. V2X Hub automatically receives and processes the arrival message from the CMV, and broadcasts a message to the CMV to instruct it to proceed to the Staging Area Pickup location to pick up a cargo specified by a provided Cargo ID.
4. The CARMA system automatically receives this instruction message from V2X Hub, generates a route to the instructed destination point, and displays a pop-up on the CARMA Web UI to prompt the test engineer to engage the system on the route to the received destination.
5. The test engineer provides user input to engage the CARMA system on the route to the received destination.

Throughout the rest of the integration test, steps 2-5 were repeated as the CARMA system proceeded to each received destination point, broadcasted its arrival, and received the next destination point. In Chapter 5, the full sequence of events are described in more detail.

By conducting proof-of-concept integration testing of the port drayage use case at the ATEF track, it was possible to determine whether the newly-developed CARMA Platform port drayage plugin and V2X Hub port drayage plugin both worked as designed. Primary responsibilities of the CARMA Platform port drayage plugin were to compose and broadcast port drayage mobility operation messages to V2X Hub to indicate the CMV’s arrival at a given destination, process received port drayage mobility operation messages from V2X Hub including destination and cargo information, generate a route to a received destination, and prompt the user to engage the CARMA System on the route to the received destination from the CARMA Web UI. With regards to the V2X Hub port drayage plugin, its primary responsibilities were to process received port drayage mobility operation messages from the CMV, compose and broadcast port drayage mobility operation messages to the CMV indicating destination and cargo information, and respond appropriately to user input provided in a port drayage web UI when loading, unloading, and inspection operations are being conducted.

In addition to enabling further development of both the CARMA Platform port drayage plugin and the V2X Hub port drayage plugin, this proof-of-concept integration testing of the port drayage use case at ATEF made it possible to identify and resolve issues in other CARMA Platform plugins that are used as part of the use case. During this integration testing phase, the following CARMA Platform packages were updated to fix issues that were identified during testing:

- Route Plugin: This plugin was updated to properly indicate when the truck has reached the end of its route when the route included at least one lane change. Prior to this change, when the truck completed a lane change and then arrived at the end of its route, no 'Route Completed' pop-up was displayed on the CARMA web UI.
- Basic Autonomy Package: This package was updated to properly plan trajectories on routes that include lane changes. Prior to this change, certain lane geometries would cause an exception in the CARMA System when beginning a lane change.

Chapter 4. Verification and Validation Testing

Testing Location

The team performed complete verification testing of the port drayage use case at the SunTrax test facility in Auburndale, Florida. SunTrax is centrally located between Tampa, Florida, and Orlando, Florida, and is being developed in two phases. The testing and development of the application occurred prior to the port management use case demo at SunTrax, and then the application was adapted for the actual demo on the closed track. An aerial view of the SunTrax test track is shown in

Figure 6.

Source: Google Earth, 2021

Figure 6. Aerial view of the SunTrax facility

Testing Set Up

The overall goal was to demonstrate a CMV operating autonomously to transport a shipping container from a port area to an offsite staging. To that end, a mock staging area and a mock port were established in suitable areas within the test facility area as shown in Figure 7.

Source: Google Earth, 2021

Figure 7. Automated CMV path at SunTrax

Verification Testing

Verification testing was performed to ensure that the system and the various port drayage plugins were built correctly, according to the system requirements outlined in the ConOps. In this project, the team tested the different actions in the port drayage use case; no loading or unloading was performed during verification. The focus was to ensure the CMV is capable of safely performing lane following, turning, communicating with CARMA Streets, and stopping and moving per instructions received from CARMA Streets. Several runs were performed and the team iteratively fine-tuned various parameters in the port drayage plugin. All actions (starting, stopping, entering staging area, exiting staging area, entering port area, exiting port area, stopping at inspection checkpoint, stopping at holding area, and the message exchange associated with each of these actions) that were considered in the integration testing stage (Chapter 3) were tested at SunTrax in a more comprehensive and complete-trip type of setting. Upon completion of the verification testing, the system was ready for validation, data collection, and analysis, which will be discussed later in the report.

Validation Testing

Following verification testing, the team performed validation testing which was led by Volpe. Validation testing was conducted by Volpe (as an independent evaluator) to confirm that the system delivers the use case according to the defined user needs and requirements which are outlined in the ConOps. In doing so, the CMV performed all actions (starting, stopping, entering staging area, exiting staging area, entering port area, exiting port area, stopping at inspection checkpoint, stopping at holding area, and the message exchange associated with each of these actions) on the SunTrax test track, and data was collected for further evaluation as discussed later in the report. In the validation testing, several aspects were evaluated as outlined and discussed in Volpe's validation report, including:

1. The system's ability to perform the port drayage operational tasks.
2. The route execution/following/communication performance.
3. The fail-safe operation of the system.

4. The system readiness for operation.

Based on the evaluation in each of these four areas, a few issues were identified and fine-tuning was performed to improve the system performance in some of the actions. For a more detailed discussion about the validation testing, please refer to the validation testing report by Volpe.

Chapter 5. Port Drayage Use Case Demonstration

Demonstration Location and Setup

Based on the results from the testing at ATEF and SunTrax facilities, the team performed the final proof-of-concept port drayage use case demonstration at the SunTrax test facility. The selected setup of the mock staging and port area at SunTrax in Figure 7 was used. In that setup, the mock staging area has an entry point, a shipping container, and exit point. The mock port has an entry point, two shipping containers, an inspection point, a holding area, and an exit point. Detailed set up for the mock staging area and port are illustrated in Figure 8. Two scenarios were considered during the use case testing at SunTrax:

1. CMV delivers containers between staging and port area with failed inspection.
2. CMV delivers containers between staging and port areas with passed inspection.

In each scenario, the CMV entered the mock staging area and was directed to a container station to wait for a container to be loaded onto a chassis attached to the CMV. The CMV was then directed to enter the mock port on a preplanned trajectory and was directed toward the appropriate container station to wait for the container to be unloaded, then to another container station to wait for a container to be loaded. The CMV then proceeded to an inspection point and waited for instructions to proceed either to the exit or to a holding area depending on whether it passed or failed the inspection. If the inspection failed, the CMV was directed to the holding area for further manual inspection before it proceeded to exit the port area. This demonstration did not consider a case where the further inspection is not satisfied.

Mock staging area

Mock port area

Source: Google Earth, 2021

Figure 8. Final setups for the mock staging and port areas

Details of the Demonstration

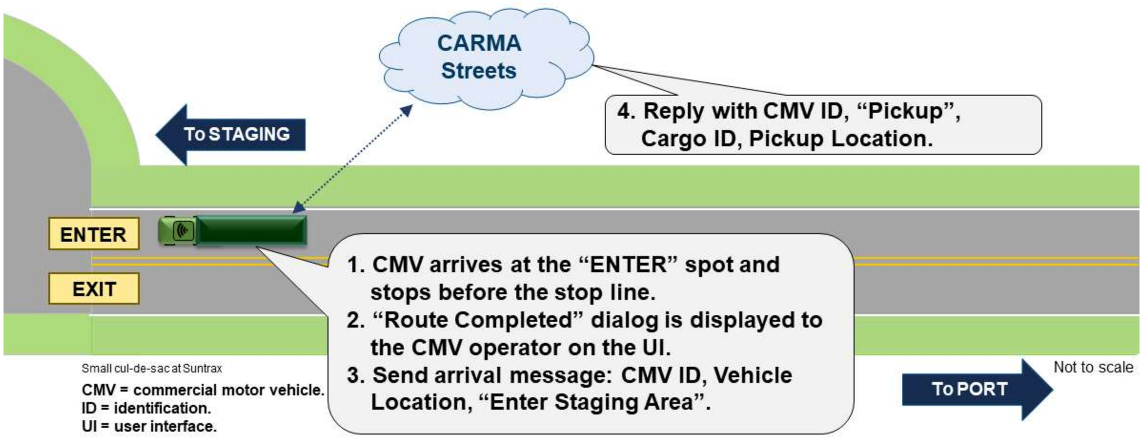
The key steps for the demonstration are listed in the following subsections. This scenario features the CMV moving a container from the staging area to the port, and another container from the port to the staging area, all in a one-round trip. This scenario makes the most efficient use of the CMV and could easily be adapted for an unloaded trip in either direction.

CMV Entering the Staging Area

The demonstration started by stationing the CMV manually at a predefined distance outside of the staging area. The CMV operator then selected the staging area entrance as the destination. The CMV accordingly started moving autonomously along a preplanned route toward the staging area. Once the CMV arrived at the staging area entrance, communication was initiated between the CMV and the infrastructure as outlined in detail in Source: FHWA, 2021

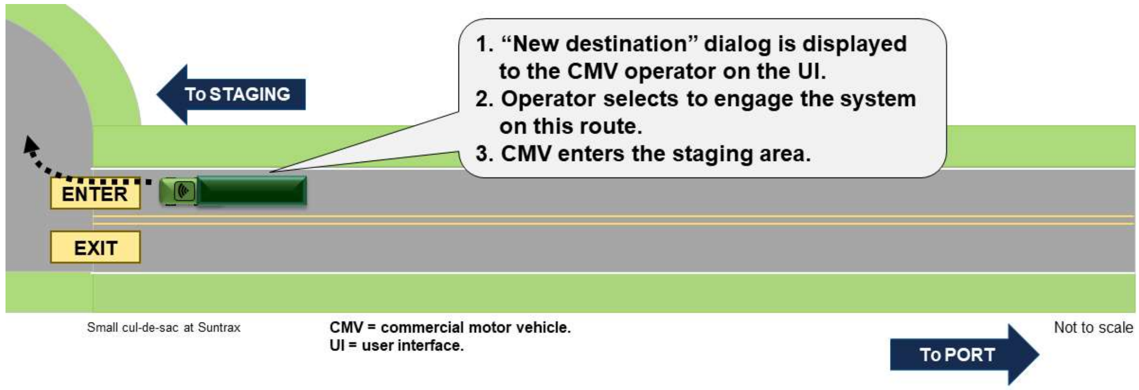
Figure 9 and Source: FHWA, 2021

Figure 10. The CMV then received instructions to enter the staging area toward a predefined location to load a container.



Source: FHWA, 2021

Figure 9. Automated CMV communicating with the infrastructure at the staging area entrance



Source: FHWA, 2021

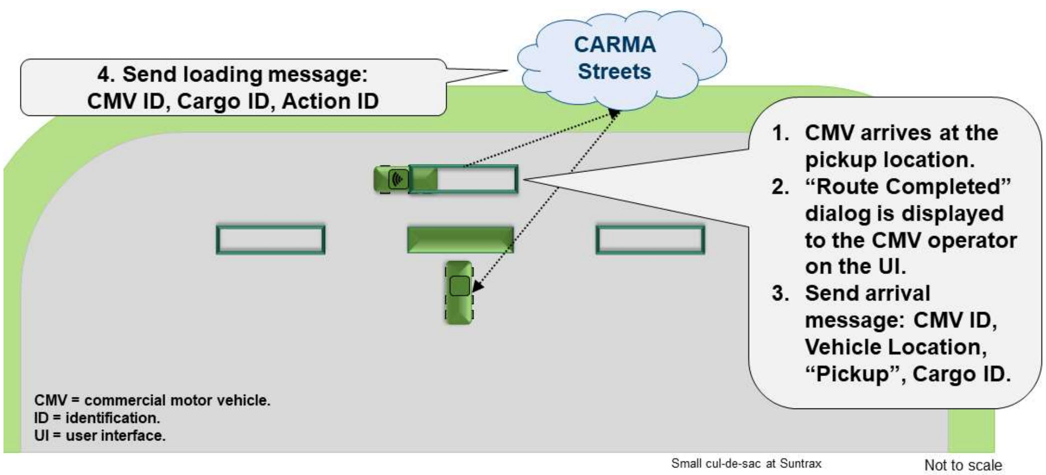
Figure 10. Automated CMV receiving instructions from the infrastructure to enter the staging area

Container Loading in the Staging Area

Upon entering the staging area, the CMV moved toward the container location for loading to begin of a container onto the CMV's chassis. Once the CMV arrived at the container location, the CMV wirelessly communicated its intent to pick up the container, and the ID of that container. The loading device then received instructions to start manual loading of the container. As the container was secured, the operator transmitted the status and the new destination to exit the staging area to the CMV. The CMV operator then selected the new destination to engage the system on the new route to exit the staging area. Details of these processes are outlined in detail in Source: FHWA, 2021

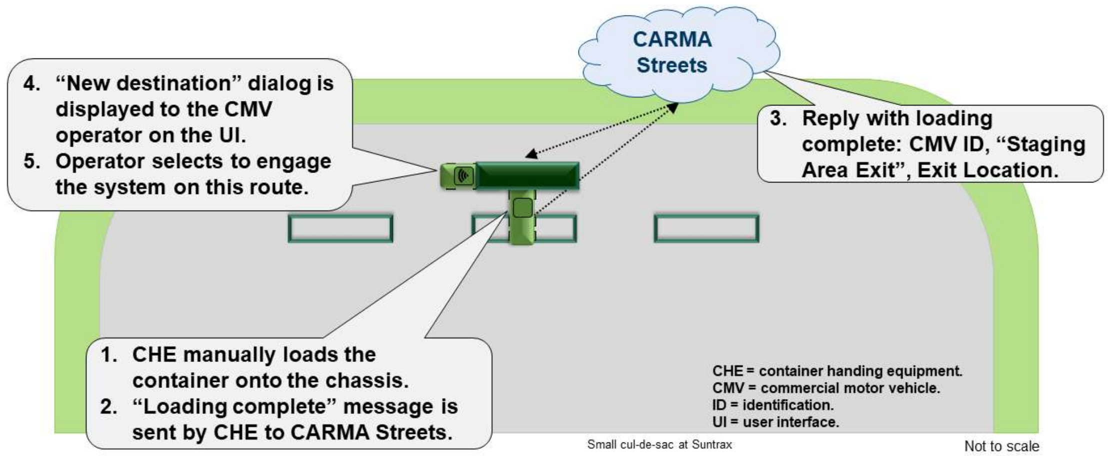
Figure 11 and Source: FHWA, 2021

Figure 12.



Source: FHWA, 2021

Figure 11. Automated CMV communicating with the infrastructure at the Container Loading Location



Source: FHWA, 2021

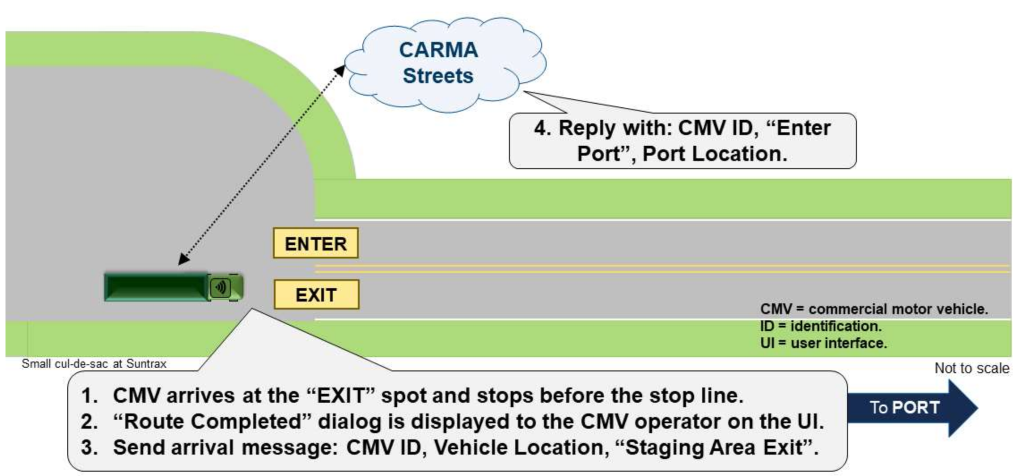
Figure 12. Automated CMV receiving loading status and instructions to exit the Staging Area from the infrastructure

CMV Exiting the Staging Area

Once the system engaged on the new destination, the CMV headed towards the staging area exit on a preplanned route. The CMV then stopped at the exit and a new two-way communication was initiated where: (1) the CMV wirelessly communicated its identifier and intent to exit the staging area, then (2) the infrastructure communicated the new destination (port area) to the CMV. Source: FHWA, 2021

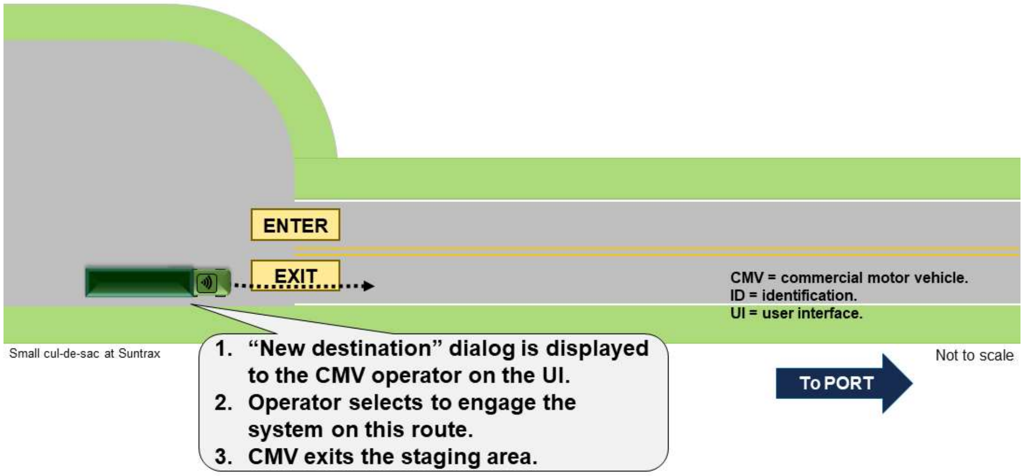
Figure 13 and Source: FHWA, 2021

Figure 14 illustrate the details of the communication between the infrastructure and CMV while exiting the staging area.



Source: FHWA, 2021

Figure 13. Automated CMV communicating its intent to exit the Staging Area with the infrastructure

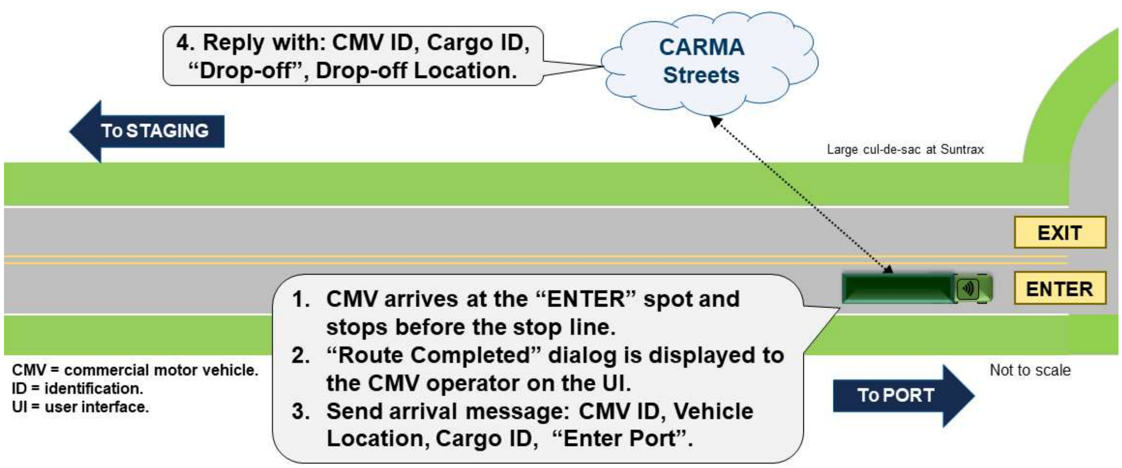


Source: FHWA, 2021

Figure 14. Automated CMV receiving instructions with a new destination to exit the Staging Area and head towards the Port Area from the infrastructure

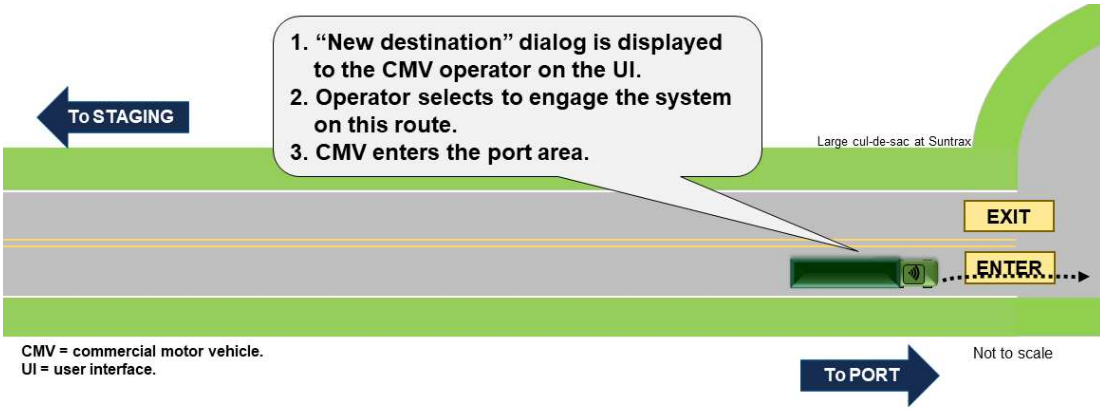
CMV Entering the Port Area

Next in the demonstration, the CMV arrived at the port area entrance and initiated communication with the infrastructure to declare its intent to deliver and unload the container it pickup from the staging area. Then, the infrastructure communicated back the new destination for the CMV to enter the port area and travel towards the container drop-off location. Figure 15 and Figure **16** illustrate the action of the automated CMV entering the port area.



Source: FHWA, 2021

Figure 15. Automated CMV communicating its intent to enter the Port Area with the infrastructure



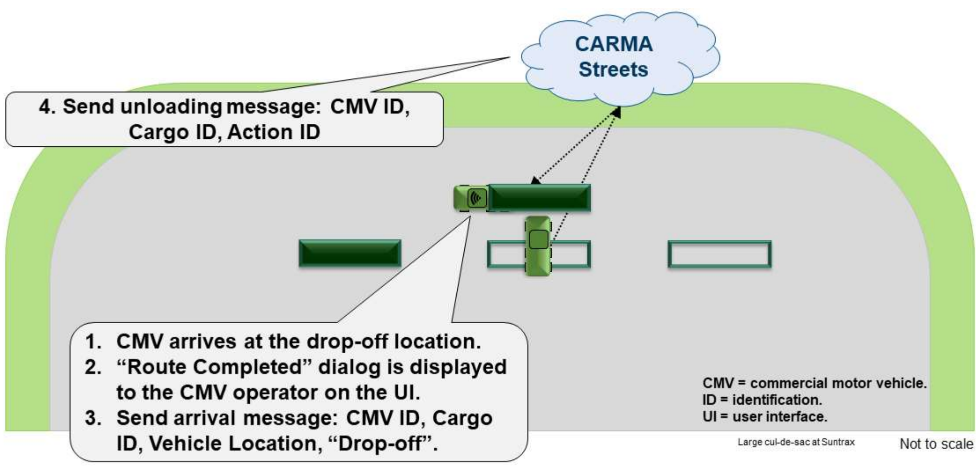
Source: FHWA, 2021

Figure 16. Automated CMV receiving instructions to enter the Port Area from the infrastructure

Container Unloading in the Port Area

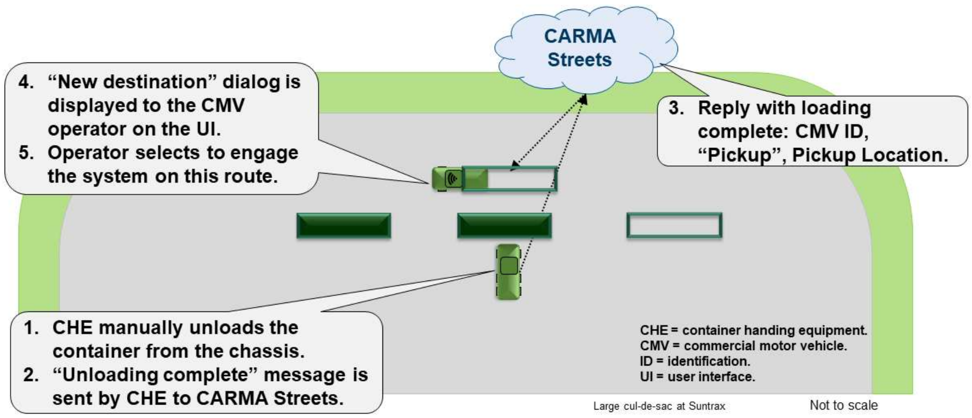
The CMV autonomously entered the port area and headed towards the container drop-off location on a preplanned route. As the CMV arrived to the drop-off destination, it communicated its intent with the infrastructure and the manual container unloading process started. Once the container unloading was completed, the operator communicated with the infrastructure which communicated a new destination to the CMV to pick up another container in the port area. Figure 17 and Figure 18Source: FHWA, 2021

Figure 18 illustrate the detailed steps of the container unloading process.



Source: FHWA, 2021

Figure 17. Automated CMV communicating its intent with the infrastructure and requesting to unload a container in the Port Area



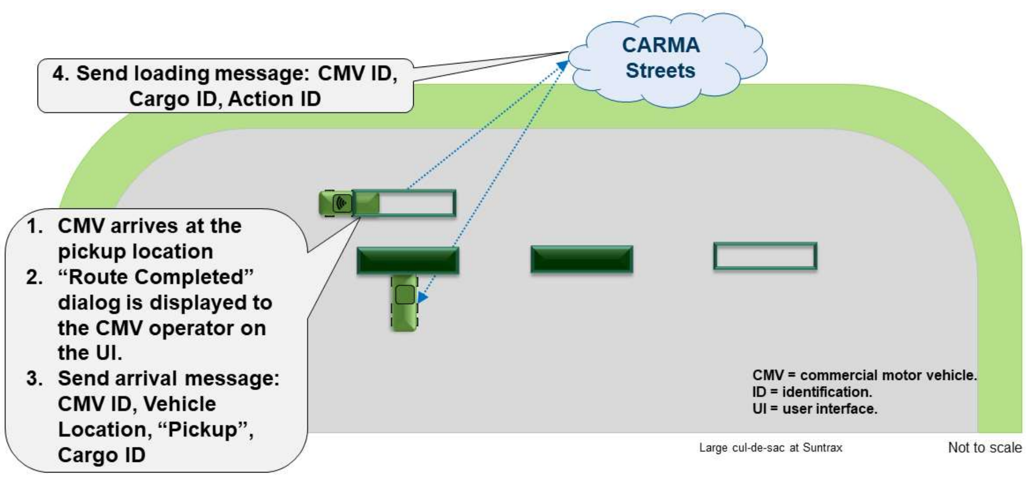
Source: FHWA, 2021

Figure 18. Automated CMV receiving unloading status and instructions to load another container in the Port Area

Container Loading in the Port Area

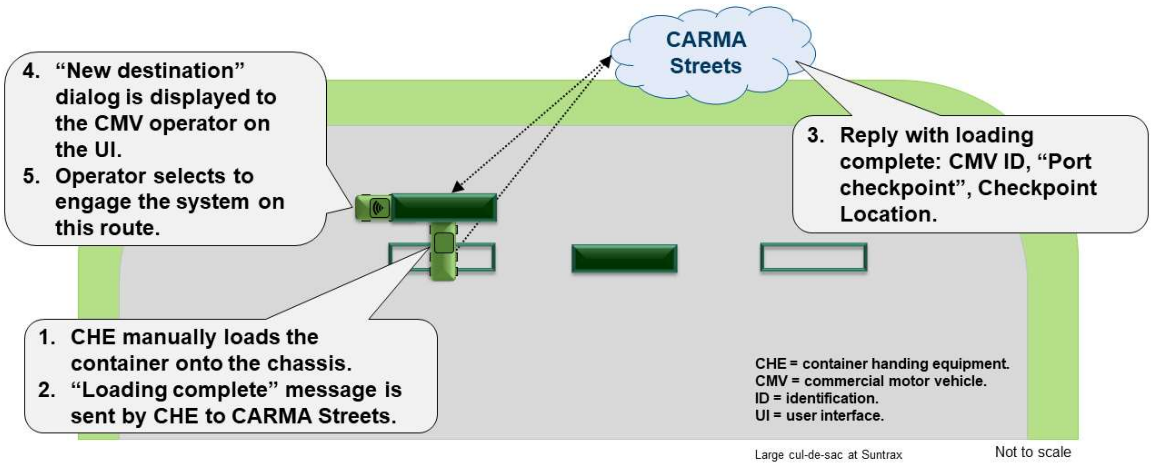
Next, the CMV headed towards and stopped at the new destination (loading location). The CMV then stopped at the container loading location and initiated communication with the infrastructure to request loading the container onto the chassis. The infrastructure then communicated with the operator to start the loading process. Once loading was completed, the operator communicated the loading status with the infrastructure which then communicated that information along with instructions to head to the inspection checkpoint to the CMV. The detailed steps and exchanged messages between the CMV and the infrastructure are illustrated in Figure 18Source: FHWA, 2021

Figure 19 Figure 19 and Figure **20**Figure 19.



Source: FHWA, 2021

Figure 19. Automated CMV communicating its intent with the infrastructure and requesting to load a container in the Port Area

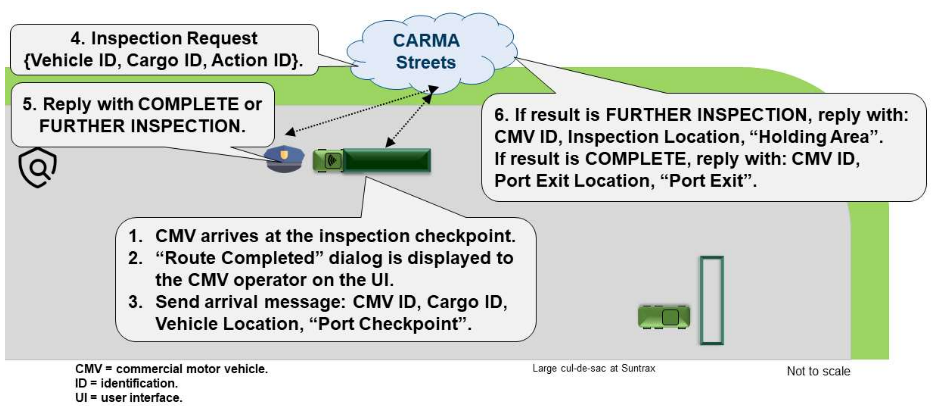


Source: FHWA, 2021

Figure 20. Automated CMV receiving loading status and instructions to head for inspection in the Port Area

CMV Arriving at the Inspection Checkpoint

Once the loading was complete, the CMV autonomously headed towards the inspection checkpoint on a preplanned route. As the CMV arrived at the inspection location, it communicated with the infrastructure its identifying information. The infrastructure then communicated an inspection request to an inspector who communicated the inspection result back to the infrastructure which communicated that along with the new destination to the CMV. The new destination was the port exit if the CMV passed the inspection, whereas the CMV was directed to a holding area for further inspection if the CMV failed the inspection. Figure 21 illustrates the steps and exchanged messages at the inspection checkpoint.

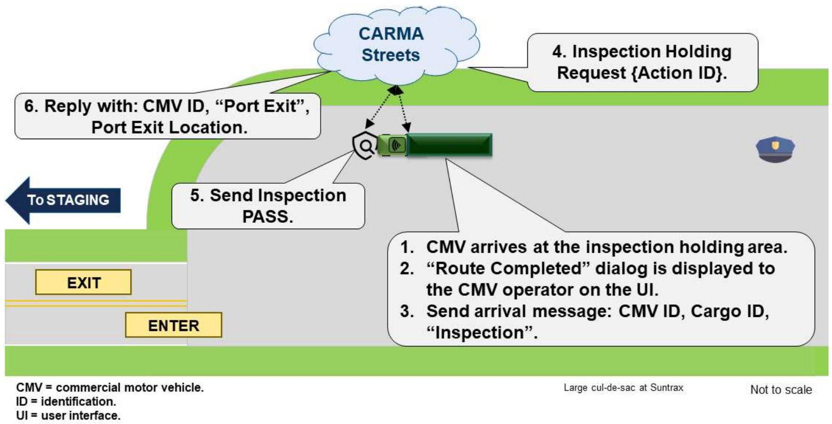


Source: FHWA, 2021

Figure 21. Automated CMV arriving at the Inspection Checkpoint

CMV Directed to the Holding Area

At the holding area, another series of communicated messages were exchanged between the CMV, infrastructure, and an inspector as illustrated in Figure 22. In this study, only the inspection passed scenario was considered at the holding area.

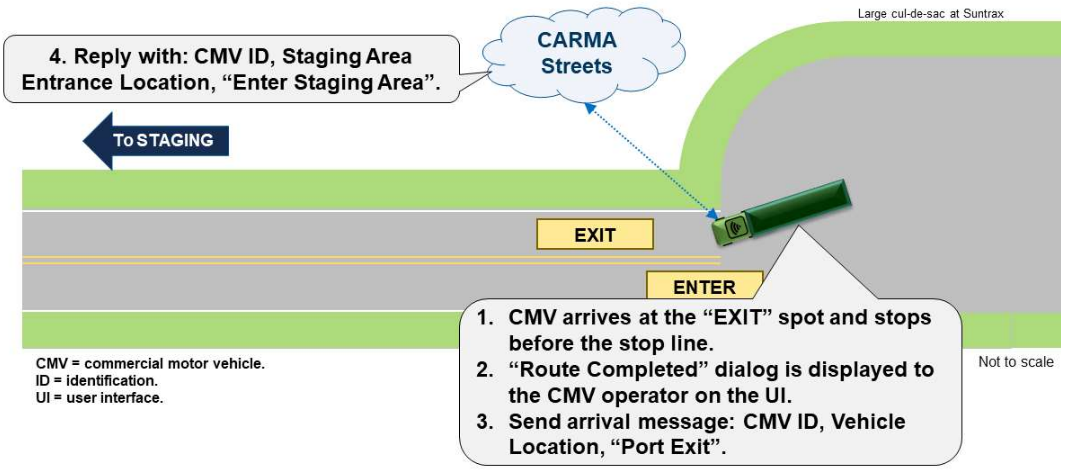


Source: FHWA, 2021

Figure 22. Automated CMV arriving at the Holding Area

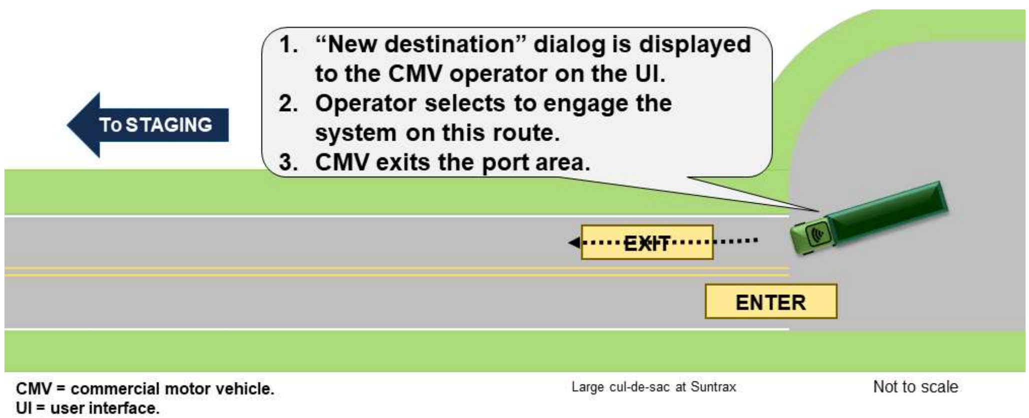
CMV Exiting the Port Area

In either scenario of whether inspection was passed at the inspection checkpoint or the further manual inspection was passed at the holding area, the CMV’s next action was to exit the port area. Once instructions to exit the port was communicated from the infrastructure to the CMV, the system was engaged for the CMV to drive autonomously to the port exit location. The CMV then stopped at the exit to communicate its identifier along with its intent to exit with the infrastructure which then communicated a new action (enter staging area) along with the new destination (staging entrance location) to the CMV. Figure **23** and Figure 24 illustrate the exchanged messages between the CMV and the infrastructure while the CMV is exiting the port area. As the CMV operator selected the new destination to engage the system to exit the port towards the staging area, the demonstration was concluded.



Source: FHWA, 2021

Figure 23. Automated CMV communicating its intent to exit the Port Area with the infrastructure



Source: FHWA, 2021

Figure 24. Automated CMV receiving instructions to exit the Port Area from the infrastructure

Chapter 6. Data Collection and Analytics

Approach and Setup for Port Drayage Performance Evaluation

In December 2021, three port drayage validation testing runs were conducted at the SunTrax test facility in Auburndale, Florida, using a single 2012 Freightliner Cascadia equipped with CARMA Platform and an attached chassis. Additionally, two hardware modules with active V2X Hub instances were set up at opposite ends of the test facility to facilitate dedicated short-range communication (DSRC) communications between the truck and the port infrastructure. The full port drayage use case includes 10 individual routes, and Figure 25 below displays an aerial image of the SunTrax test facility with each sequential route start point labelled 0-to-9.

Source: Google Earth, 2021

Figure 25. Automated CMV path at SunTrax for the Port Drayage use case with sequential route start points labeled

A description of each route's start and end points is provided in

Table 1 below. While the port drayage demonstration includes an additional route from the “Port Checkpoint” to the “Port Exit” in the case of a completed inspection at the checkpoint, this route was not included in validation testing, and has been omitted from

Table 1.

Table 1. Description of Port Drayage validation testing route start and stop locations

Route ID	Start Location	Stop Location
0	Use Case Start Point (~150 meters before Staging Area Entrance)	Staging Area Entrance
1	Staging Area Entrance	Staging Area Pickup
2	Staging Area Pickup	Staging Area Exit
3	Staging Area Exit	Port Entrance
4	Port Entrance	Port Dropoff
5	Port Dropoff	Port Pickup
6	Port Pickup	Port Checkpoint
7	Port Checkpoint	Port Holding Area
8	Port Holding Area	Port Exit
9	Port Exit	Staging Area Entrance

In order to quantify the CARMA system's overall ability to perform the port drayage use case, several metrics were developed. Using an automated data analysis script that processes rosbags from CARMA Platform, each individual evaluation run conducted during validation testing was analyzed using these metrics. Table 2 displays the number of metrics developed for the port drayage use case, along with the number of port drayage evaluation runs that were conducted for validation testing.

Table 2. Description of Port Drayage route start and stop locations

Use Case	Number of Metrics Evaluated	Number of Evaluation Runs Conducted
Port Drayage	25	3

The metric results for the evaluation runs are presented and discussed in more detail within the following subsections.

Port Dryage Evaluation Results

The tables below show the results for the 25 metrics that were evaluated for the port drayage use case evaluation runs. Each table includes a description of a specified metric, the applicable route IDs from

Table 1, the results of the metric, and additional notes pertaining to the results of the metric, if available.

The applicable route IDs for each metric were agreed upon with project stakeholders prior to validation testing. Since the number of applicable route IDs differs between metrics, each metric's table can have a different number of total evaluated routes in its "Results" cell. Since three validation testing evaluation runs were conducted, the total number of evaluated routes for each metric is a multiple of three and the number of applicable route IDs.

Table 3. Port Drayage Metric 1 Results

Freight Port Drayage Metric 1: Vehicle achieves its target speed. Expected Value: +/- 2 mph of the speed limit			
Truck Tested	Applicable Route IDs	Results	Additional Notes
2012 Freightliner Cascadia (Silver Truck)	0	3/3 Successful	The speed limit for this route was 20 mph.

Table 4. Port Drayage Metric 2 Results

Freight Port Drayage Metric 2: The vehicle is able to stop at the Port or Staging Area Entry without passing the entry. Expected Value: +0/-3 Meters (Front Bumper Position)			
Truck Tested	Applicable Route IDs	Results	Additional Notes
2012 Freightliner Cascadia (Silver Truck)	0, 3	0/6 Successful	This metric was finalized after testing was completed, and a feature within CARMA Platform had not yet been included in the system design to stop a vehicle with its front bumper positioned at a route end point. During validation testing, CARMA Platform was designed to stop a truck with the center of its cab's rear axle positioned at the route end point, which resulted in the front bumper being positioned past the route end point. In January 2022, the CARMA Platform design was updated to stop a truck with the center of its front bumper positioned at a route end point. Related CARMA Platform GitHub Issue: #1462

Table 5. Port Drayage Metric 3 Results

Freight Port Drayage Metric 3: The vehicle is able to exit the Port or Staging Area when instructed by the infrastructure. Expected Value: Yes

Truck Tested	Applicable Route IDs	Results	Additional Notes
2012 Freightliner Cascadia (Silver Truck)	3, 9	6/6 Successful	N/A

Table 6. Port Drayage Metric 4 Results

Freight Port Drayage Metric 4: The speed limit while note inside the Port or the Staging Area Expected Value: 20 – 25 mph			
Truck Tested	Applicable Route IDs	Results	Additional Notes
2012 Freightliner Cascadia (Silver Truck)	0, 3	6/6 Successful	The speed limit for these sections of the use case was 20 mph.

Table 7. Port Drayage Metric 5 Results

Freight Port Drayage Metric 5: The vehicle is able to stop at the inspection point without passing the inspection point and wait for the next destination. Expected Value: +0/-3 Meters (Front Bumper Position)			
Truck Tested	Applicable Route IDs	Results	Additional Notes
2012 Freightliner Cascadia (Silver Truck)	6	0/3 Successful	This metric was finalized after testing was completed, and a feature within CARMA Platform had not yet been included in the system design to stop a vehicle with its front bumper positioned at a route end point. During validation testing, CARMA Platform was designed to stop a truck with the center of its cab’s rear axle positioned at the route end point, which resulted in the front bumper being positioned past the route end point. In January 2022, the CARMA Platform design was updated to stop a truck with the center of its front bumper positioned at a route end point. Related CARMA Platform GitHub Issue: #1462

Table 8. Port Drayage Metric 6 Results

Freight Port Drayage Metric 6: The test operator can select the destination for the vehicle to be either the holding area or the Port exit. Expected Value: Yes			
Truck Tested	Applicable Route IDs	Results	Additional Notes

2012 Freightliner Cascadia (Silver Truck)	6	3/3 Successful	N/A

Table 9. Port Drayage Metric 7 Results

Freight Port Drayage Metric 7: The vehicle is able to stop at the holding area without passing the holding area and wait for further instructions. Expected Value: +0/-3 Meters (Front Bumper Position)			
Truck Tested	Applicable Route IDs	Results	Additional Notes
2012 Freightliner Cascadia (Silver Truck)	7	0/3 Successful	This metric was finalized after testing was completed, and a feature within CARMA Platform had not yet been included in the system design to stop a vehicle with its front bumper positioned at a route end point. During validation testing, CARMA Platform was designed to stop a truck with the center of its cab’s rear axle positioned at the route end point, which resulted in the front bumper being positioned past the route end point. In January 2022, the CARMA Platform design was updated to stop a truck with the center of its front bumper positioned at a route end point. Related CARMA Platform GitHub Issue: #1462

Table 10. Port Drayage Metric 8 Results

Freight Port Drayage Metric 8: The vehicle is able to drive the route to the destination provided by infrastructure once the user engages on the route from the Web UI. Expected Value: Yes			
Truck Tested	Applicable Route IDs	Results	Additional Notes
2012 Freightliner Cascadia (Silver Truck)	1, 4, 5, 6, 7, 8	18/18 Successful	N/A

Table 11. Port Drayage Metric 9 Results

Freight Port Drayage Metric 9: The infrastructure is able to communicate the next destination to the vehicle. Expected Value: Yes			
Truck Tested	Applicable Route IDs	Results	Additional Notes
2012 Freightliner Cascadia	0, 2, 3	9/9 Successful	N/A

(Silver Truck)			

Table 12. Port Drayage Metric 10 Results

Freight Port Drayage Metric 10: The vehicle is able to receive the next destination from the infrastructure and display a message on the Web UI to the user to proceed to that destination point Expected Value: Yes			
Truck Tested	Applicable Route IDs	Results	Additional Notes
2012 Freightliner Cascadia (Silver Truck)	1, 2, 3, 4, 5, 6 7, 8, 9	27/27 Successful	N/A

Table 13. Port Drayage Metric 11 Results

Freight Port Drayage Metric 11: The vehicle is able to stop at the container loading/unloading point within the margin of error. Expected Value: +0/10 Meters (Front Bumper Position)			
Truck Tested	Applicable Route IDs	Results	Additional Notes
2012 Freightliner Cascadia (Silver Truck)	1, 4, 5	0/9 Successful	This metric was finalized after testing was completed, and a feature within CARMA Platform had not yet been included in the system design to stop a vehicle with its front bumper positioned at a route end point. During validation testing, CARMA Platform was designed to stop a truck with the center of its cab’s rear axle positioned at the route end point, which resulted in the front bumper being positioned past the route end point. In January 2022, the CARMA Platform design was updated to stop a truck with the center of its front bumper positioned at a route end point. Related CARMA Platform GitHub Issue: #1462

Table 14. Port Drayage Metric 12 Results

Freight Port Drayage Metric 12: The test operator is able to communicate to infrastructure that the container is loaded. Expected Value: Yes			
Truck Tested	Applicable Route IDs	Results	Additional Notes
2012 Freightliner Cascadia	1, 5	6/6 Successful	N/A

(Silver Truck)			

Table 15. Port Drayage Metric 13 Results

Freight Port Drayage Metric 13: The infrastructure is able to communicate to the vehicle that the container is loaded. Expected Value: Yes			
Truck Tested	Applicable Route IDs	Results	Additional Notes
2012 Freightliner Cascadia (Silver Truck)	1,5	6/6 Successful	N/A

Table 16. Port Drayage Metric 14 Results

Freight Port Drayage Metric 14: The infrastructure is able to communicate to the vehicle that the container is unloaded. Expected Value: Yes			
Truck Tested	Applicable Route IDs	Results	Additional Notes
2012 Freightliner Cascadia (Silver Truck)	4	3/3 Successful	N/A

Table 17. Port Drayage Metric 15 Results

Freight Port Drayage Metric 15: The infrastructure is able to communicate to the test operator a loading message. Expected Value: Yes			
Truck Tested	Applicable Route IDs	Results	Additional Notes
2012 Freightliner Cascadia (Silver Truck)	1, 5	6/6 Successful	N/A

Table 18. Port Drayage Metric 16 Results

Freight Port Drayage Metric 16: The infrastructure is able to communicate to the test operator an unloading message. Expected Value: Yes			
Truck Tested	Applicable Route IDs	Results	Additional Notes
2012 Freightliner Cascadia (Silver Truck)	4	3/3 Successful	N/A

Table 19. Port Drayage Metric 17 Results

Freight Port Drayage Metric 17: The test operator is able to communicate to infrastructure that the container is unloaded. Expected Value: Yes			
Truck Tested	Applicable Route IDs	Results	Additional Notes
2012 Freightliner Cascadia (Silver Truck)	4	3/3 Successful	N/A

Table 20. Port Drayage Metric 18 Results

Freight Port Drayage Metric 18: The vehicle is able to send an arrival message to the infrastructure. Expected Value: Yes			
Truck Tested	Applicable Route IDs	Results	Additional Notes
2012 Freightliner Cascadia (Silver Truck)	0, 1, 2, 3, 4, 5, 6 7, 8	27/27 Successful	N/A

Table 21. Port Drayage Metric 19 Results

Freight Port Drayage Metric 19: The speed limit while inside the Staging Area or Port. Expected Value: 10 mph			
Truck Tested	Applicable Route IDs	Results	Additional Notes
2012 Freightliner Cascadia (Silver Truck)	1, 2, 4, 5, 6, 7, 8	24/24 Successful	N/A

Table 22. Port Drayage Metric 20 Results

Freight Port Drayage Metric 20: The vehicle is able to receive mobility operations messages from infrastructure. Expected Value: Yes			
Truck Tested	Applicable Route IDs	Results	Additional Notes
2012 Freightliner Cascadia (Silver Truck)	1, 2, 3, 4, 5, 6, 7, 8, 9	27/27 Successful	N/A

Table 23. Port Drayage Metric 21 Results

Freight Port Drayage Metric 21: After the CMV has broadcasted its arrival message to V2XHub, the CMV shall receive a valid response from V2XHub including the next instructed destination in less than 1.5 seconds. Expected Value: < 1.5 Seconds			
Truck Tested	Applicable Route IDs	Results	Additional Notes
2012 Freightliner Cascadia (Silver Truck)	1, 3, 4, 9	12/12 Successful	On average, the CMV received a response from V2XHub within 0.09 seconds.

Table 24. Port Drayage Metric 22 Results

Freight Port Drayage Metric 22: After the CMV has received a message from V2XHub instructing it to proceed to its next destination, the CMV shall successfully generate an active route to that destination in less than 3 seconds. Expected Value: < 3 Seconds			
Truck Tested	Applicable Route IDs	Results	Additional Notes
2012 Freightliner Cascadia (Silver Truck)	1, 2, 3, 4, 5, 6, 7, 8, 9	27/27 Successful	On average, the CMV successfully generated an active route to the received destination in 0.13 seconds.

Table 25. Port Drayage Metric 23 Results

Freight Port Drayage Metric 23: After the CMV is engaged on the route to its next destination, the CMV's actual trajectory will include an acceleration section. The average acceleration over the entire section shall be no less than 1.0 m/s^2, and the average acceleration over any 1-second portion of the section shall be no greater than 2.0 m/s^2. Expected Value: >= 1 m/s^2 for full section, and <= 2.0 m/s^ for any 1-second portion.			
Truck Tested	Applicable Route IDs	Results	Additional Notes
2012 Freightliner Cascadia (Silver Truck)	0, 1, 2, 3, 4, 5, 6, 7, 8, 9	0/30 Successful	The average acceleration across all evaluated routes was 0.58 m/s^2, which is below the threshold specified for this metric. Additional parameter tuning could be conducted in order to improve the performance of the system with regards to this metric. Related CARMA Platform GitHub Issue: #1637

Table 26. Port Drayage Metric 24 Results

Freight Port Drayage Metric 24: As the CMV approaches its destination, the CMV's actual trajectory will include a deceleration section. The average deceleration over the entire section shall be no less than 1.0 m/s^2, and the average deceleration over any 1-second portion of the section shall be no greater than 2.0 m/s^2. Expected Value: >= 1 m/s^2 for full section; <= 2.0 m/s^2 for any 1-second portion.			
Truck Tested	Applicable Route IDs	Results	Additional Notes
2012 Freightliner Cascadia (Silver Truck)	0, 1, 2, 3, 4, 5, 6 7, 8	0/27 Successful	10 of 27 evaluated routes included a total average deceleration below 1.0 m/s^2, with an average across these runs of 0.75 m/s^2. These low deceleration rates occurred for Route IDs 1, 5, 6, and 7, since the truck began its end-of-route deceleration from a lower speed on these Route IDs than for the others. This lower speed was a result of the route end points being placed after segments of road curvature that the CARMA System had decreased its planned speed for in order to comfortably steer through. 22 of 27 evaluated routes included a 1-second deceleration above 2.0 m/s^2 at the end of the route, with an average across these runs of 2.52 m/s^2. Similar to the previous statements regarding the total average deceleration rate, Route IDs 1, 5, and 6 had instances that satisfied this metric since the truck began its end-of-route deceleration from a lower speed on these Route IDs than for the others. Additional parameter tuning could be conducted in order to improve the performance of the system with regards to this metric. Related CARMA Platform GitHub Issue: #1545

Table 27. Port Drayage Metric 25 Results

Freight Port Drayage Metric 25: After the CMV arrives at its destination, the UI shall successfully show a "Route Completed" dialog. Expected Value: < 3 Seconds

Truck Tested	Applicable Route IDs	Results	Additional Notes
2012 Freightliner Cascadia (Silver Truck)	0, 1, 2, 3, 4, 5, 6 7, 8	27/27 Successful	On average, the UI displayed a "Route Completed" dialog 0.06 seconds after the CMV arrived at its destination.

Identified Issues and Next Steps

In total, three port drayage evaluation runs were conducted and analyzed using 25 separate metrics. Of the 25 metrics, 19 were 100 percent successful, and 6 were 0 percfent successful. Altogether, the 6 metrics that were not 100 percent successful can be consolidated into three separate issues. These three issues, along with proposed approaches to resolve them, are listed in Table 28.

Table 28. Issues identified from Port Drayage evaluation results

Issue Number	Issue Description	Related Port Drayage Metric(s)	Proposed Approach for Issue Resolution
1	The CARMA system is designed to stop a truck with the center of its cab's rear axle positioned at a route end point. This results in the front bumper of the truck being positioned beyond the route end point.	2, 5, 7, 11	As of January 2022, this issue was resolved. The CARMA system design was updated to stop a truck with the center of its front bumper – rather than the center of its cab's rear axle—positioned at a route end point. CARMA Platform GitHub Issue #1462 can be referenced for this issue.
2	During acceleration sections, the vehicle accelerates at an average rate lower than 1.0 m/s^2.	23	Additional parameter tuning could be conducted in order to increase the average acceleration rate of the system. Related CARMA Platform GitHub Issue: #1637
3	When decelerating to a complete stop, the vehicle stops abruptly at the end of this deceleration section. This results in a 1-second deceleration rate of above 2.0 m/s^2 at the end of the stop.	24	Additional parameter tuning could be conducted in order to reduce the deceleration rate of the system when coming to a complete stop. CARMA Platform GitHub Issue #1545 exists to track this issue.

Chapter 7. Conclusion

This project demonstrated the use of CDA for port drayage as part of the Cooperative Driving Automation Port Drayage Development and Testing Initiative. The objective is to further the technology implementation in our nation's ports to accelerate the adoption of the technologies available, and to point out the benefits cooperative driving automation can bring to our nation's ports.

The project demonstrated application of connectivity and automation for trucks transporting containers between a staging area and a port area. Other actions the automated truck performed include loading, unloading, going through inspection at the port, and following instructions to go through further inspection at a holding area withing the port. The required software development of the port drayage plugin and web UI was performed, the plugin was tested at ATEF and SunTrax, and the complete use case was demonstrated at SunTrax, in Auburndale, Florida.

Data were collected for multiple runs of the use case, and they were analyzed to evaluate the system's ability to perform the port drayage operational tasks while engaged, the route following performance, route execution performance, and communication performance. The evaluation was performed based on a set of performance metrics that were developed by the team.

The evaluation showed that the automated truck was able to pass the majority of the performance metrics in all test runs. However, a few metrics that are relevant to the truck's stopping, acceleration, and deceleration behavior showed that additional work is yet required for the use case to be fully ready. Nonetheless, testing and demonstration of the use case showed no safety concerns that could prevent further development or consideration of other freight-related use cases.

This use case proved the benefits that could be realized through application of CDA in the U.S. ports. While port drayage is one process that involves many challenges related to congestion, air quality, and potentially safety, the use case point out many areas of benefits. First, the communication involved in CDA between the automated truck and the infrastructure is key to support the complex logistics within the U.S. ports to guide drives/operators on when/where they should move the trucks. Second, the path planning required for the movement of the automated truck is another crucial element to enable optimal and safe movement of the drayage trucks within the port and between the port and staging area. Third, through communication and automation, the trucks can be alert and responsive to changing conditions at the ports, hence congestion could be managed and all the associated impacts (e.g. emissions) could be addressed.

Overall, this project helped to develop a better understanding of the benefits that could be realized by applying CDA to port drayage. While there were a few limitations identified through data collection and analysis, no safety concerns were raised and high potential for future work remains intact. In essence, various applications could be developed and tested for port drayage and short haul including enhanced port demonstration (which is the next stage of this project), signal preemption, and many others.

References and Notes

[1] For the definition of drayage, visit: https://www.definitions.net/definition/drayage

[2] Some large container terminals have "on-dock rail" and containers are loaded/unloaded from the trains by terminal container handling equipment and no truck drayage is needed.

[3] In larger U.S. ports approximately 15-26 percent of the containers handled by the marine container terminals are transported by rail to or from the container terminals.

[4] Containers are designed so that container seals (one-time door locks) can be used to secure the handles attached to the locking rods that keep the containers closed. For the locking rods to be rotated into the open position, the seals on the handles must be cut off.

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U.S. Department of Transportation
ITS Joint Program Office – HOIT
1200 New Jersey Avenue, SE
Washington, DC 20590

Toll-Free "Help Line" 866-367-7487

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