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

Concept of Operations for Enhanced Automated Port Drayage

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Notice

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16. Abstract

The Federal Highway Administration (FHWA) Office of Safety and Operations Research and Development (HRSO) performs transportation operations research and development (R&D) at the Saxton Transportation Operations Laboratory (STOL), established at the Turner-Fairbank Highway Research Center (TFHRC). In support of common goals, the Federal Motor Carrier Safety Administration (FMCSA) and the Maritime Administration (MARAD) have partnered with FHWA and STOL to explore the application of cooperative automation to Commercial Motor Vehicle (CMV) operations. Four CMVs have been 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.

The purpose of this task is to leverage cooperative driving automation for port drayage operation which involves interaction of a commercial motor vehicle (CMV) with a container terminal's infrastructure to perform loading and unloading of containers, inspection, and passage through port and staging area gates. This document describes the concept of operations for an enhanced automated port drayage use case tailored for the APM terminal in Mobile, AL. A detailed discussion is given of the required changes and associated benefits to enable the proposed concept. Finally, a detailed discussion of the needs and requirements to implement the proposed changes for automated port drayage operation at APM terminal is outlined.

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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.)

Foreword

The Federal Highway Administration (FHWA) Office of Safety and Operations Research and Development (HRSO) performs transportation operations research and development (R&D) at the Saxton Transportation Operations Laboratory (STOL), established at the Turner-Fairbank Highway Research Center (TFHRC). In support of common goals, the Federal Motor Carrier Safety Administration (FMCSA) and the Maritime Administration (MARAD) have partnered with FHWA and STOL to explore the application of cooperative automation to Commercial Motor Vehicle (CMV) operations. Four CMVs have been 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.

One area where the STOL sees the opportunity for improvement is with traffic congestion at the nation's ports. This document outlines a concept that applies automation to the commercial motor vehicles that perform drayage operations at ports. The purpose of this task is to leverage cooperative driving automation for port drayage operation, which involves interaction of a commercial motor vehicle (CMV) with a container terminal's infrastructure to perform loading and unloading of containers, inspection, and passage through port and staging area gates.

This document provides a general look into how the concept of automated drayage may apply to any port terminal. FHWA looks forward to exploring the concept further with its partners at FMCSA and MARAD.

Brian Cronin
Director
Office of Safety and Operations Research and Development

Quality Assurance Statement

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Table of Contents

List of Tables

List of Figures

Executive Summary

Purpose

This study focuses on application of automation to the commercial motor vehicles (CMVs) that perform drayage operations at ports. This document is a concept of operations (ConOps) of an enhanced automated port drayage application that presents key aspects of how connected automated CMVs would function in this situation.

Process

This study represents an initial examination of the application of connected automated CMVs for container drayage operations to and from marine container terminals. The study process includes the following steps:

First, the ConOps explores current drayage operations at existing container terminals. The ConOps explores major stakeholders, objects, and subjects, and identifies opportunities for improvements.

Second, the ConOps provides a justification for the recommended changes and the nature of the changes.

Third, the ConOps introduces the concept and describes it in detail, including end-to-end scenarios that illustrate use of the proposed improvements. The ConOps recognizes limitations and impacts.

Finally, the ConOps identifies a list of requirements for implementation of the concept.

Rationale and Background

The Intelligent Transportation Systems Maritime Administration (ITS MARAD) program is a joint U.S. Department of Transportation (USDOT) initiative. It is co-led by the Intelligent Transportation Systems-Joint Program Office (ITS–JPO) and MARAD, with modal participation from the Federal Highway Administration (FHWA) and the Federal Motor Carrier Safety Administration (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 identify a portfolio of projects that agencies, including port authorities, can implement through advanced transportation and congestion management technologies deployment (ATCMTD) 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 container terminals. In May 2019, the program completed the ITS MARAD Truck Staging Study, including an economic feasibility study of several container terminal and truck queuing solutions. The program is working with relevant maritime stakeholders to ensure effective technology transfer activities of the completed products and tools and is developing plans for future evaluation activities.

The Port Cooperative Driving Automation Drayage Truck Development and Testing initiative is a demonstration of automated driving systems (ADS) in a port environment in a multiyear project to increase efficiencies, increase safety, and decrease emissions. The project objective is to further technology implementation in our Nation's ports to accelerate adoption of the available technologies, and to investigate the costs and benefits of automated truck movement in queues at ports and staging areas or warehouses. The project will develop and demonstrate a concept of connected vehicles and autonomous vehicle technology applications with gate passage, inspection point passage, short-haul drayage, and loading and unloading of containers to and from chassis.

The primary motivation for the proposed concept is to address truck congestion on container terminal access roads and at terminal gates. The congestion is caused by trucks queuing at the container terminal gates due to operational congestion within the container terminals, as well as trucks arriving before the container terminal gates are open. Congestion-related delays are a main cause of lost productivity of drayage truck drivers. In addition to lost productivity, congestion causes several externalities, such as environmental degradation and shipment cost increases. This document discusses key challenges with current container terminal drayage operations that underscore the need for improvements. This document also discusses the nature of changes to operations, technology, and management required to support the proposed concept. Finally, the document provides a list of requirements for implementation of the concept.

Deployment Strategies

The project team plans to demonstrate the concept described in this document using two avenues: a scale model and an actual port facility. Prior to those efforts, a proof of concept will have been demonstrated on a closed track. The team submitted a generic version of this report in March 2020, which discussed a generic ConOps for this project. The team has updated this edition of the report to configure the ConOps to work with a specific container terminal, APM Terminal in Mobile, Alabama. A first phase of the demonstration will use scale model trucks operating around a scale model port, with a layout based on the APM Terminal. This demonstration will carry out the key operations of gate passage, inspection point passage, short-haul drayage, and loading and unloading of containers to and from chassis. This would be a limited implementation of the proposed concept to serve as a basic demonstration of the capabilities.

A recommendation for future work is to carry out a field test at an existing container terminal. APM Terminal has agreed to partner with the project team for the small-scale demonstration, but not yet for the full-scale demonstration. While the project team would first approach APM terminal for this work, their cooperation is not guaranteed. Thus, phase 2 may involve several additional steps prior to implementation, including seeking out a port authority and a container terminal operator to cooperate and provide resources. Future research teams can compile a set of required and desired container terminal characteristics to assist in selection. Once a team has demonstrated the concept at an existing container terminal and port area, researchers can consider a more widescale deployment.

Chapter 1. Introduction

Background

The Federal Highway Administration (FHWA) Office of Safety and Operations Research and Development (HRDO) performs transportation operations and research and development at the Saxton Transportation Operations Laboratory (STOL), established at the Turner-Fairbank Highway Research Center. The Government has many projects underway that use agile software development practices to create open-source software with robust communities of practice. Each project supports different parts of an overall intelligent transportation systems (ITS) deployment architecture and is managed separately with individual development teams. In support of common goals, the Federal Motor Carrier Safety Administration (FMCSA) and Maritime Administration (MARAD) have partnered with FHWA and STOL to explore the application of cooperative automation to commercial motor vehicle (CMV) operations. Four CMVs are being equipped with automation technologies, including CARMA, to enable an SAE International® (SAE) Level 2–3 operation, furthering research opportunities and capabilities available to FMCSA, MARAD, and the Government [1].

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

- Identify opportunities to conduct research that addresses key freight movement and ITS infrastructure gaps.
- Identify opportunities for pilot projects and programs to be deployed, including technology transfers.

The Intelligent Transportation Systems Maritime Administration (ITS MARAD) program is a joint U.S. Department of Transportation (USDOT) initiative. It is co-led by 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 identify a portfolio of projects that agencies, including port authorities, can implement through advanced transportation and congestion management technologies deployment (ATCMTD) 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 container terminal and truck queuing solutions [2]. The program is working with relevant maritime stakeholders to ensure effective technology transfer activities of the completed products and tools and is developing plans for future evaluation activities.

The Port Cooperative Driving Automation Drayage Truck Development and Testing initiative is a demonstration of automated driving systems (ADS) in a port environment in a multiyear project to increase efficiencies, increase safety, and decrease emissions. The project objective is to further technology implementation in our Nation’s ports to accelerate adoption of available technologies, and to investigate the costs and benefits of automated truck movement in queues at ports and staging areas or warehouses. The project will develop and demonstrate a concept of connected vehicles and autonomous vehicle technology applications with gate passage, inspection point passage, short-haul drayage, and loading and unloading of containers to and from chassis.

The current effort, Development of Cooperative Automation Capabilities: Integrated Prototype II, is producing the next iteration of CARMA. CARMA3 takes the platform into the world of ADS with SAE Level 3 automation. The approach takes advantage of an open-source ADS platform to enable ADS functionality for cooperative automation strategies. This work builds upon and extends the research from Prototype II that developed CARMA Platform℠, CARMA Cloud℠, and CARMA Simulation. This project focuses on enhancing CARMA Platform, CARMA Cloud, and CARMA Simulation through agile software development to support ADS transportation systems management and operations (TSMO) use cases. The products of these efforts will enable the work under this task order.

Overview

The purpose of this task is to use cooperative driving automation to interact with a container terminal's infrastructure to increase the efficiency of container drayage within a port area. In this task, small-scale model autonomous trucks will demonstrate the technology's ability to navigate and function within a container terminal and on public roads. The project team will model the container terminal and associated public roads at a test facility where the small-scale model trucks will be operated. The modelled container terminal's layout, dimensions, operations (including gate controls, container loading/unloading, inspections, and others), and data flow will reflect the actual container terminal that was selected. This small-scale model testing will lay the groundwork for potential future tasks of digital traffic flow simulation of drayage operations, and a live full-scale demonstration of container drayage using the fleet of four CARMA-equipped heavy vehicles. Federal agencies coordinating on the project include ITS–JPO, MARAD, FHWA, and FMCSA.

The key objectives of this task are to:

- Work with a port partner to demonstrate connected vehicles and autonomous vehicle technology applications with gate passage, inspection point passage, short-haul drayage, and loading and unloading of containers to and from chassis.
- Build upon and extend the research from Prototype II that developed CARMA Platform, CARMA Cloud, and CARMA Simulation.
- Focus on enhancing CARMA Platform, CARMA Cloud, and CARMA Simulation through agile software development to support ADS TSMO use cases.

This document describes a concept for improving container drayage efficiency at container terminals and in the port areas. The project team studied drayage operations at container terminals and the surrounding port areas to determine where vehicle automation could improve efficiency. Given the generic concept of operations (ConOps) to test cooperative driving automation, the team developed this related ConOps to work with a specific container terminal. This document lists high-level requirements for implementing the concept on a large scale.

Audience

The intended audience for this document includes:

- USDOT cooperative automation and freight operations stakeholders.
- System developers who will implement and support operations based on the concept described in this document.
- Port and terminal owners and operators, and stakeholders across the larger freight network.
- Analysts, researchers, and connected automated vehicle (CAV) application developers.

Document Overview

The structure of this document is generally consistent with the outline of a System Operational Concept document, described in “Annex A” of *ISO/IEC/IEEE Standard 29148:2011*. In U.S. transportation systems engineering practice, this is called a ConOps document, and that title is included in this document. The project team enhanced some sections to accommodate more detailed content than is described in the standard, as well as edited some of the section titles to more specifically capture those enhancements.

Chapter 1 provides a background of the project and defines the scope of the ConOps.

Chapter 2 describes the current situation of container terminal operations and drayage and identifies key players and stakeholders in those activities.

Chapter 3 describes the limitations of the current situation that drive the need for the proposed changes and describes the nature of those changes.

Chapter 4 presents the concept for automated container terminal drayage—describing the capabilities and operations of the concept—and a detailed description of operational scenarios.

Chapter 5 provides a list of high-level requirements for the proposed system.

Chapter 6 provides a list of reference documents.

System Overview

This study focuses on improving the efficiency of container drayage to and from marine container terminals through the use of CAVs. Marine container terminals are complex, and they vary in design to suit the needs of each port. While the primary goal of all marine container terminals is to move goods, factors such as location, size, and demand drive key differences in the operations. For instance, wheel-based terminals store containers on a chassis (trailers designed to transport container), whereas stacked-facility (or ground-based) terminals store containers in stacks several high on the ground. Wheel-based facilities require larger space proportionally than stacked-container terminals to operate, so they are more feasible at ports with lower container volumes. Some facilities stack most of their containers but maintain a wheeled section for specific customers. Since the study will demonstrate CAVs that are not capable of hitching and unhitching to a chassis, wheel-based container terminals are not suitable for this project. The project team selected APM Terminal in Mobile, Alabama, (figure 1) as a basis for model testing because it is a well-documented typical stacked container terminal. Moreover, the terminal has recently expanded to incorporate state-of-the-art technology and practices.

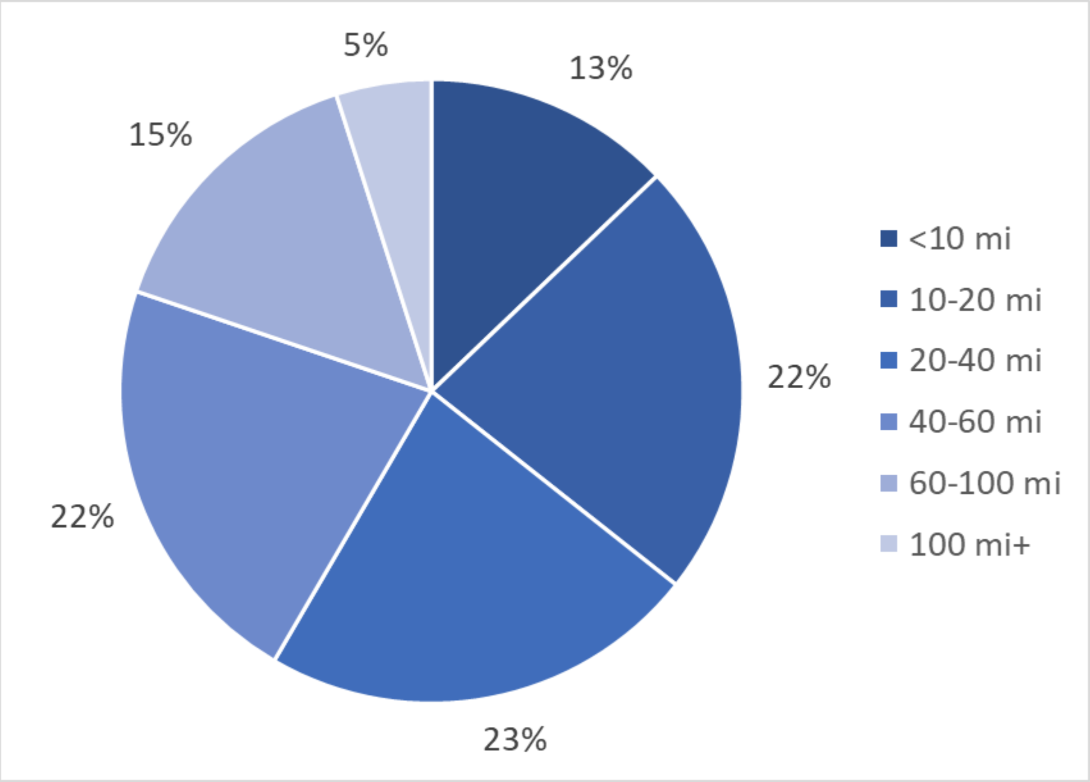
© Google® Earth™, 2021. [3]

Figure 1. Photograph. APM Terminal Mobile.

This APM Terminal has a nearly balanced shipment of import and export containers. Most drayage operation at this terminal are double moves, in that the truck will enter the terminal with an export container that will be lifted off the chassis and an import container will then be loaded onto that chassis. If a truck needs to hook up to chassis, that operation is conducted at an off-site chassis depot (no chassis hooking or unhooking is done on the container terminal).

The difference between a container being drayed and a container transported over the road (OTR) is based on the distance involved; however, there is no universally adopted parameter that provides the dividing line between drayage and OTR. Drayage distances vary by port. As an example, Source: Adapted from Calstart 2013. [7]

Figure 2 illustrates the typical drayage distances in southern California. A National Cooperative Freight Research Program Project reported that the average drayage radius was 48–60 miles for the Port of Houston and less than 75 miles for the Port of New York-New Jersey [4]. In regard to the APM Terminal selected, a review of the Drayage Directory for the Port of Mobile indicates that 22 percent of the container drays (one way) were less than 60 miles, 12 percent were 60–150 miles, 37 percent were 151–249 miles, and 28 percent were more than 250 miles [5]. Almost all drayed containers involve being transported between: 1) a consignee or consignor and the container terminal, 2) a container terminal and a rail intermodal terminal, or 3) from one container terminal and another container terminal in the same or nearby port [6].

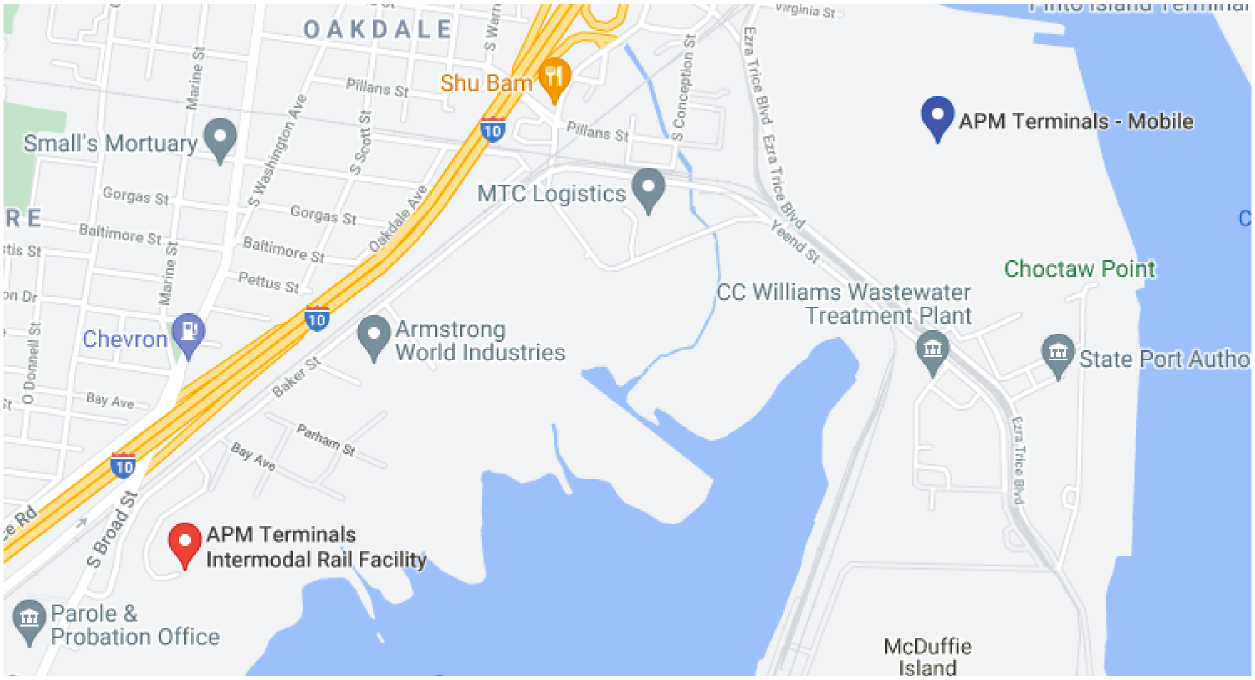


Source: Adapted from Calstart 2013. [7]

Figure 2. Pie Chart. Typical drayage distances for the Ports of Los Angeles and Long Beach.

While there are many container terminal configurations, the selected terminal is typical of a stacked container terminal. This project will focus on autonomous truck operations within the container terminal and to and from a point outside the terminal where container transport will continue by manually controlled trucks or other modes of transportation. This transition point will be referred to as the control handover point. The control handover point that will be used for the APM Terminal demonstration will be a rail intermodal terminal located less than 2 miles from the container terminal, as shown in © Google® Maps™, 2021. [3]

Figure 3. This rail intermodal terminal will ultimately have the capacity to handle 200,000 twenty-foot equivalent units (TEU) a year, which would be about 15 percent of the container terminal's total capacity (based on 2019 total TEU handled, this equates to 83,992 TEUs, or about 50,000 containers). Using the CAVs to dray containers to the rail intermodal terminal represents a possible real-world scenario.



© Google® Maps™, 2021. [3]

Figure 3. Map. Proximity of the rail intermodal facility and the container terminal.

The automated trucks will operate in mixed traffic in the terminals and on the 2 miles of public road between them. The CAVs will be processed through the same terminal gates and checkpoints used by existing drayage trucks.

System Benefits

The use of CARMA-equipped heavy vehicles for container drayage to and from container terminals has the potential to reduce congestion in the terminals. This can in turn reduce truck queuing times at the terminal's gates and congestion on the approach roads cause by the trucks waiting to enter the terminal. (The APM Terminal selected does not currently have a congestion problem and it is being used as a test bed for proof of concept.) Less congestion can reduce truck turn times and emissions from idling trucks, and can improve throughput capability of container terminals. Realizing this potential requires that the CARMA-equipped trucks communicate with the mobile container handling equipment (CHE) (e.g., straddle carriers, stackers, forklifts) and other trucks in the terminal either directly or through a yard management system operated by the terminal operators. CARMA Platform will enable the drayage truck to select the optimum route to the designated container drop-off or pickup location. On average each container in a stacked container terminal is required to be moved three times by mobile CHE before it is loaded onto a truck, so the mobile equipment on the terminal is constantly in motion. The CARMA-equipped truck being fed information from 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 select an alternative route. This reduces congestion on the terminal. Additionally, having both the truck and the CHE aware of each other's movement and intentions can reduce the potential for collisions, thereby improving worker safety in the terminal.

The CARMA components and features will interact to achieve these benefits. The CARMA ecosystem includes technologies for both vehicles (CARMA Platform and CARMA Messenger) and the infrastructure (CARMA Streets and CARMA Cloud). In addition to the benefits outlined in the prior paragraph, CARMA Platform-equipped trucks can benefit from the following sequence of activities:

1. Navigate safely on public roads.
2. Request and receive a gate appointment time.
3. Provide truck and container identification (ID) and electronic shipping documents for the cargo.
4. Stop at the gate for security inspection and proceed when cleared.
5. Obtain container loading and/or unloading location.
6. Obtain information on available traffic routes (driving map) within the terminal.
7. Receive updates from the terminal regarding changes to the driving map.
8. Receive traffic information about the movement/activities of CHE and other trucks on the terminal to optimize the routes to take within the terminal to deliver and/or pick up containers and the routes to depart.
9. Receive traffic information updates while in the terminal.
10. Recognize operating characteristics of CHE (e.g., footprint, how it maneuvers, speed, time to perform operations, safe distances to maintain, blind spots).
11. Report location, activity, speed, and load condition to the terminal.
12. Pass under the radiation portal monitor (RPM) (some units require the truck to stop while others allow the truck to proceed at a set speed). If the RPM alerts, the truck needs to either remain in place or go to a specified location for secondary inspection; once cleared the truck should resume its trip.
13. Stop at the exit gate for release. Electronically convey truck and container information to the terminal.

In step 8, CARMA Platform-equipped trucks can obtain relevant data (e.g., location, itinerary) from other connected trucks via CARMA Messenger. All of the above steps involve some level of information exchange with the infrastructure. CARMA Cloud can manage rules and logistics for the majority of these information exchanges. However, to ensure safe and efficient traffic flow, CARMA Streets can help to manage vehicle conflict points within the terminal.

Chapter 2. Current Situation

The main operational domain of this ConOps is container terminal drayage. To understand how connectivity and automation can improve efficiency and operations of this domain, the ConOps must define the current system. This section describes the stakeholders, objects, operational spaces, and interactions associated with drayage operations. After defining all aspects of the current system, the chapter provides an example narrative of a vehicle operator through a typical drayage operation.

Stakeholders

Container terminal drayage of cargo containers involves interactions among six stakeholder groups: 1) customers, 2) ocean carriers, 3) terminal operator management and employees, 4) port/dock workers, 5) trucking firms, and 6) Federal agencies. Within each stakeholder group, there are several actors. The following section describes each stakeholder group and the relevant actors within the groups.

Customers

The customer's objective is to have cargo moved through a container terminal. Movement of a customer's cargo is the fundamental reason for terminal operations. Actors within this stakeholder group may include the following:

- Beneficial cargo owners: Beneficial cargo owners are the ultimate owners of the cargo. They may directly coordinate with the port terminal to export or import their goods, or they may contract out to an importer, exporter, or third-party logistics (3PL) firm.
- Importers: The primary objective of importers (also known as a consignee) is to receive goods at their preferred time and at the lowest possible cost.
- Exporters: The primary objective of exporters (also known as a consigner) is to ship goods at their preferred time and at the lowest possible cost.

Ocean Carriers

Ocean carriers are responsible for port-to-port marine transportation. While ocean carriers are a key stakeholder in the drayage process, this ConOps focuses on drayage after the cargo has been unloaded from a ship or just before it is loaded.

Terminal Operators Management and Employees

Terminal operators management and employees work directly for the terminal owners. They are responsible for coordinating all activities within the port terminal, including directing port/dock workers. They interact with all stakeholders and actors to facilitate efficient transportation of goods. The main goal of terminal operators is to efficiently move cargo through the container terminal at the lowest possible cost.

Port/Dock Workers

Port/dock workers are on-the-ground workers who perform specific tasks to directly move cargo, or facilitate movement of cargo, through the marine terminal as directed by terminal management. The workers may be directly employed by the terminal, or they may work gangs provided by union dispatch halls. Most terminals of significant size in the United States use unionized longshoremen, machinist, and clerks.

Trucking Firms and Integrated Service Providers

In the context of this ConOps, a trucking firm's primary responsibility is movement of cargo during drayage; 3PLs may also perform this function. These firms are independent of the container terminal and may be responsible for transporting goods beyond the terminal. Actors in this stakeholder group include the following:

- Drayage operators: Drayage operators are responsible for operating a Class 8 truck within the port terminal. They will pick up and/or drop off a shipping container during drayage and make two or more trips a day.
- OTR operators: Similar to drayage operators, OTR operators drive Class 8 trucks hauling containers. However, the main difference between OTR and drayage operators is the distance the operator hauls the container. OTR operators generally drive 500 miles or more a day.
- 3PLs: These are contracted by cargo owners to arrange or provide transportation of their goods. 3PLs may conduct drayage or OTR shipments and may coordinate warehousing of the cargo owner's goods.

Federal Agencies

The primary responsibility of Federal agencies is to ensure compliance with regulations and Federal law. Some actors in this stakeholder group are directly involved in drayage, while others enforce regulations that extend beyond drayage activities. Drayage is only a portion of the greater freight shipping domain; the following is a non-exhaustive list of Federal agencies involved in freight shipping:

- **U.S. Department of Homeland Security (DHS), primarily U.S. Customs and Border Protection (CBP) and the U.S. Coast Guard:** primarily responsible for knowing what is inside a container, whether it poses a risk to people, and ensuring proper revenues are collected. DHS is actively involved in drayage operations by processing all containers through checkpoints such as RPM.
- **FMCSA:** primary mission is to reduce crashes, injuries, and fatalities involving large trucks and buses. While not directly involved with drayage, FMCSA's rules and regulations can have a significant

influence on drayage throughput. For example, hours of service regulations limit the duration drivers are allowed to operate a vehicle or be on duty. This can lead to complications with drayage planning because of long delays drivers might encounter while waiting their turn in the staging area.

Objects

Objects are aspects of container terminal operations that require manipulation from an actor, such as ships, cranes, or manual trucks, to transport goods. Objects are tools that facilitate increased container terminal efficiency and throughput.

International Standards Organization Containers

International Organization for Standardization (ISO) containers are stackable intermodal containers suitable for shipment by ship, rail, or truck. Containers are between 20–45 feet long and 8.6–9.6 feet high. Some 53-foot-long intermodal containers are shipped on certain domestic routes. There are 53-foot-long containers that are transported by rail and truck that cannot be loaded on a ship because they cannot be stacked more than two high when loaded. Trucks are required to pull a chassis or a flatbed trailer to transport ISO containers.

Class 8 Trucks

Class 8 trucks have the highest gross vehicle weight rating (GVWR). Class 8 is subdivided into Class 8a and Class 8b [8]. Class 8a trucks have a GVWR of 33,001–60,000 pounds. Trucks used in container drayage are generally Class 8b and will have a GVWR of more than 60,000 pounds. The effects of automation applied to these trucks is the focus of this drayage ConOps.

Container Chassis

A container chassis is a trailer designed to be hauled by a truck and is designed specifically to transport ISO containers. Prior to 2010 most chassis were provided by the ocean carriers and were picked up and returned to the container terminals. Most chassis today are provided by independent chassis pools and are picked up and returned to chassis depots located outside the container terminal. There has also been an increase in dray trucking firms buying or long-term leasing chassis in order to avoid the time spent picking up a chassis from a pool or returning it [9]. Most container chassis are designed for either 40- or 20-foot intermodal containers. However, other chassis types exist, such as those designed for less common container sizes, self-loading chassis, and extendable chassis. This ConOps focuses on the use of 40-foot container chassis.

Container Handling Equipment

Container handling equipment (CHE) are objects that move intermodal containers within the port. Example movements are loading/unloading ocean carriers or moving containers to staging locations. This ConOps focuses on handling equipment used to load and unload containers during drayage. Examples of CHE include the following:

- Quay cranes: Quay cranes load and unload containers to and from a ship or container barge. Quay cranes move on rails that run along the dock, parallel to the ship being loaded or unloaded. The cranes can reach across the width (beam) of the ship. They are able to lift containers from the dock and place them in or onto the ship, or do the reverse when unloading containers. Longshoremen operate these cranes. Alternatively, in small operations, ships equipped with cranes (geared ships) can load or unload containers, or general purpose portable cranes will be used to load ships.
- Straddle carriers: Straddle carriers are tall vehicles that lift and move containers within a terminal after or before the containers have been loaded onto an ocean carrier. A straddle carrier whose wheelbase is wider than a container drives over (i.e., straddles) a container, and then lifts it so it can be moved or stacked on top of another container. It is also possible for a straddle carrier to drive directly above a container chassis to load or unload a container.
- Forklifts: Forklifts are typically the smallest and most mobile form of CHE in terminal operations. In the context of this ConOps, forklifts are considered any piece of CHE capable of loading containers onto chassis and that has rear-wheel steering, such as top-pick empty handlers, reach stackers, and side loaders.

Operational Space

Functional and physical spaces vary among ports, which influences the operation of a port’s drayage activities. Drayage operations can be categorized into three distinct areas: 1) inside the gate, 2) transition, and 3) outside the gate. Operations that occur inside the marine terminal gate include all activities related to loading and unloading the ocean carrier. CBP has jurisdiction over cargo within the gate and can authorize its release, inspect it there, or transport it to a nearby central examination center. The transition area includes the movement of cargo between the marine terminal and the external road network. Outside the gate includes all activities related to transporting and delivering cargo to the receiving company. Transitions between these phases involve the physical movement and legal responsibility for transfer of the cargo. Table 1 illustrates the three drayage operational areas and stakeholders involved in a generic container terminal design.

Table 1. Container terminal stakeholders and areas of operation and responsibility.

Inside the Gate	Transition (Inside-Outside)	Outside the Gate
• Ocean carriers • Marine terminal operators • Trucking firms/operators • Railroads • Chassis pool operators • CBP	• Trucking firms/operators • Railroads • Chassis pool operators	• Trucking firms/operators • Railroads • Chassis pool operators • Shipper/receivers • State and city departments of transportation • Metropolitan planning organizations

Source: FHWA, 2022.

Table 2 illustrates the three drayage operational areas and stakeholders involved in the selected container terminal. APM Mobile does not have a chassis pool in the container terminal. There is a new rail intermodal terminal very close to the container terminal; however, the tracks do not actually enter the container terminal. While CBP is the Nation's primary border control organization, numerous other agencies have the authority to place shipments on hold either directly or through CBP.

Table 2. APM Mobile stakeholders and areas of operation and responsibility.

Inside the Gate	Transition (Inside-Outside)	Outside the Gate
• Ocean carriers • Marine terminal operators • Trucking firms/operators • U.S. Government	• Trucking firms/operators	• Trucking firms/operators • Railroads • Chassis pool operators • Shipper/receivers • State and city law enforcement • Metropolitan planning organizations

Source: FHWA, 2022.

Port Drayage Transactions

There are four primary transaction types during drayage: 1) tractor hauling a loaded container, 2) tractor hauling an empty container, 3) tractor pulling a chassis with no container, and 4) tractor with no trailer (also known as bobtail). These are only representative of typical or ideal transactions. There are several exceptions to these transactions, such as equipment issues and errors in transactions. These four transaction types result in eight routine transactions, as shown in Table 3.

Table 3. Routine entry and exit transaction types.

Transaction Types		Entry			
		Bobtail	**Bare Chassis**	**Empty on Chassis**	**Load on Chassis**
Exit	**Bobtail**	Bobtail in Bobtail out	Chassis in Bobtail out	Empty in Bobtail out	Export in Bobtail out
	Bare Chassis	Bobtail in Chassis out	Chassis in Chassis out	Empty in Chassis out	Export in Chassis out
	Empty on Chassis	Bobtail in Empty out	Chassis in Empty out	Empty in Empty out	Export in Empty out
	Load on Chassis	Bobtail in Import out	Chassis in Import out	Empty in Import out	Export in Import out

Source: Tioga Group, University of Texas at Austin, and University of South Carolina, Truck Drayage Productivity Guide, 2011. [10]

On the terminal selected, there are fewer primary transactions because they do not store chassis on the terminal, and most of their transactions involve the drayage truck delivering a container and receiving a container (double move). Consequently, there are no bobtail transactions. The entry and exit transaction types are summarized in Table 4.

Table 4. APM Mobile entry and exit transaction types.

Transaction Type [11]	Truck Enters Terminal with	Truck Departs Terminal with
Loaded in/out ≈ 30%	Loaded export	Loaded import
Empty in, loaded out ≈ 30%	Empty container	Loaded import
Loaded in, empty out ≈ 20%	Loaded export	Empty container
Chassis in, empty out ≈ 10%	Unladed chassis	Empty container
Chassis in, loaded out ≈ 10%	Unladed chassis	Loaded import

Source: FHWA, 2022.

Drayage Processes

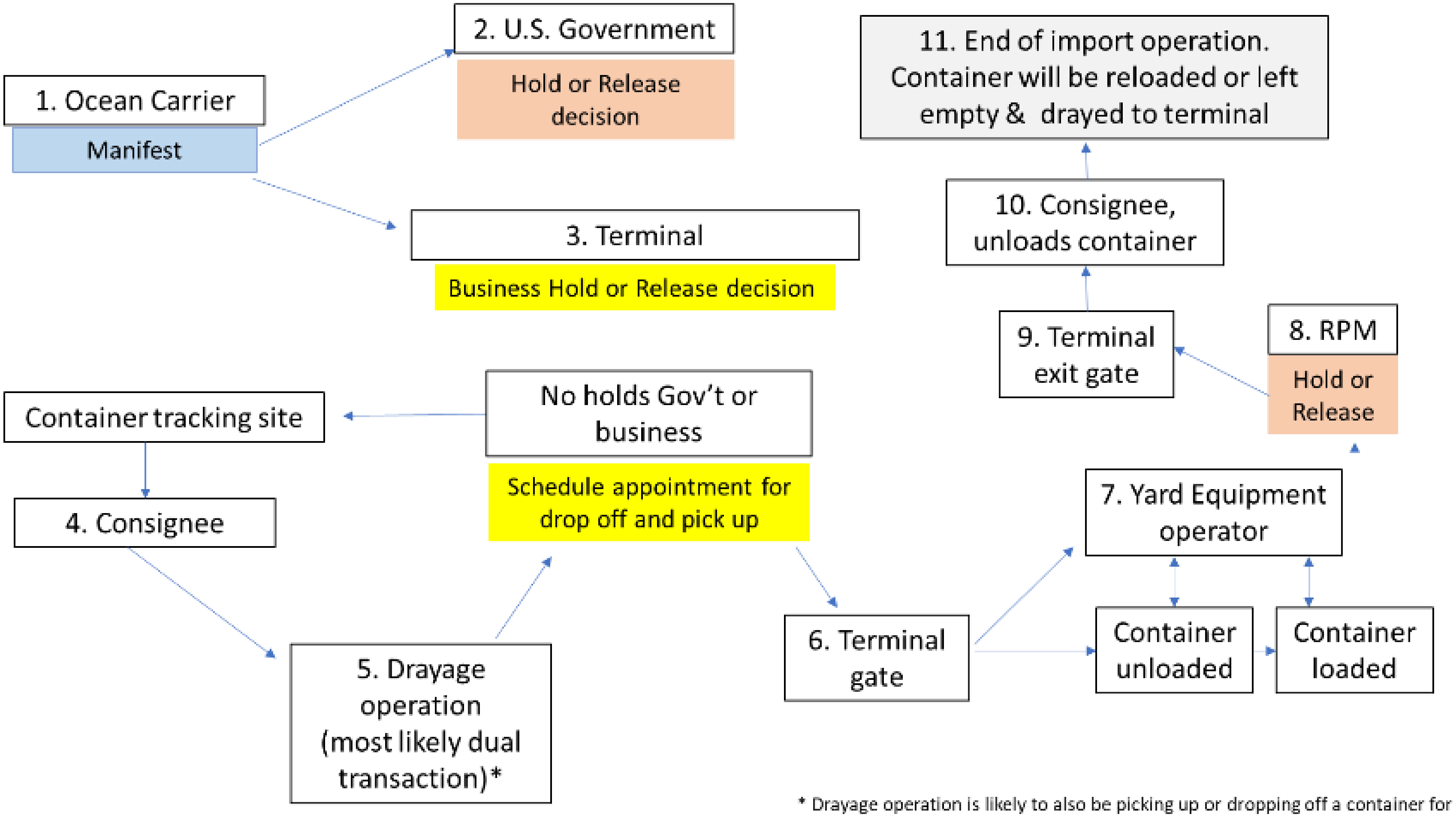
Within the scope of this ConOps, drayage consists of two main processes and one sub-process. The two main processes are import drayage and export drayage; the sub-process is the CBP container checkpoint.

Import Drayage Process

As shown in figure 4, there are 11 steps in the import drayage process, with five stakeholders involved: the shipping line, drayage firm, terminal, consignee, and the Government.

Export Drayage Process

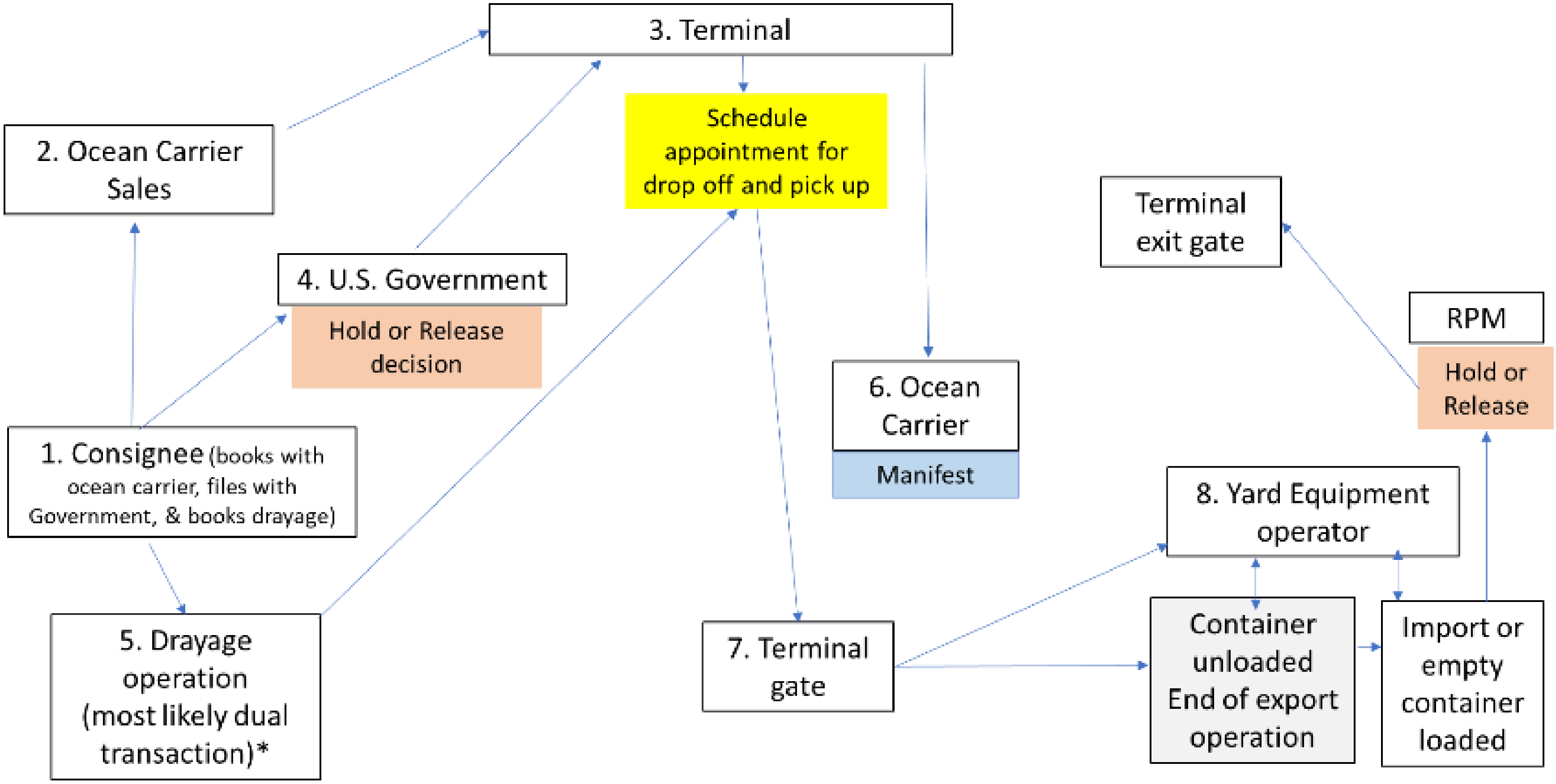
As shown in figure 5, there are eight steps in the export drayage process, with four stakeholders involved: the shipper, drayage firm, terminal and the Government. Consignees are irrelevant because they are only involved in receiving goods.



* Drayage operation is likely to also be picking up or dropping off a container for another customer so that the truck is employed both ways (in and out)

Source: FHWA, 2022.

Figure 4. Diagram. Import drayage process.



* Drayage operation is likely to also be picking up or dropping off a container for another customer so that the truck is employed both ways (in and out)

Source: FHWA, 2022.

Figure 5. Diagram. Export drayage process.

Radiation Portal Monitor Processing

As described in the *Federal Agencies section*, CBP is the foremost agency involved with screening and inspecting containers. These screenings and inspections seldom impact container drayage, with the exception of requiring containers to be driven through an RPM. Normally if a container has been targeted for inspection (i.e., it has not “cleared customs”) it will be put on hold and the terminal operator will not authorize a dray driver to enter the port to retrieve the container [12].

RPM is a non-intrusive means of detecting elevated levels of radiation. During RPM processing, a truck with a container drives through the RPM, which can detect unusually high levels of radiation to identify illicit nuclear materials. “If an alarm is triggered, the cargo container or vehicle is directed to a secondary area for further inspection and clearance by a CBP officer using a handheld radiation detector that can identify the source of the radiation” [13] (see Source: Government Accountability Office, 2016. [13]

Figure 6). DHS reported that, historically, less than 2 percent of cargo containers have set off an RPM alarm. To reduce nuisance alarms and decrease secondary scanning by CBP officers, in 2014 and 2015 CBP developed and deployed a new set of RPM alarm threshold settings, with support from the Domestic Nuclear Detection Office (DNDO) and Pacific Northwest National Laboratory. This upgrade, which is referred to as revised operational settings, is implemented during calibration. It optimizes RPM effectiveness by tuning the threshold settings of individual RPMs to account for local background radiation and common naturally occurring radiative material passing through the RPMs. These new threshold settings result in a similar sensitivity to materials that pose a threat but significantly reduce nuisance alarms from naturally occurring radiative material. According to CBP, as of the end of fiscal year 2015, DNDO and CBP had upgraded RPMs at 28 seaports and 15 land border crossings, which has reduced nuisance alarms at these sites by more than 75 percent on average. Before fiscal year 2015, DHS had acquired 1,706 RPMs.

Source: GAO. | GAO-17-57

Source: Government Accountability Office, 2016. [13]

Figure 6. Photographs. Radiation portal monitor (left) and secondary inspection.

Chapter 3. Potential for Automation in Drayage Operations

The primary motivation for the proposed concept is to reduce truck congestion on container terminal access roads, at gates, and within the terminals, as well as reduce drayage delays within terminals. Congestion-related delays are a main cause of lost productivity of drayage truck drivers. Congestion also causes several externalities, such as environmental degradation and shipment cost increases. This chapter discusses key challenges in container terminal operations that underscore the need for the concept proposed in this document. It also discusses the nature of operations, technology, and management changes required to support the proposed concept.

Introduction to Current Challenges

"Due to growing transport volumes, environmental restrictions, and port competition, the productivity and efficiency of port operations needs to be further enhanced to increase the competitiveness of seaports" [14]. Truck traffic congestion at many seaports has greatly increased. There has been rapid worldwide growth in seaborne trade for the past several decades. From 2008 to 2018, total goods loaded, worldwide, grew from 8,231 to 11,005 million tons, averaging an annual increase of approximately 3 percent [15]. While most tonnage is in the form of bulk liquids and solids, such as petroleum, grain, and iron ore, there has also been a vast increase in the number of intermodal shipping containers moved. Between 2010 and 2018, the number of containers shipped rose from 560 to 793 million TEUs (a measure of the number of containers shipped) per year—an increase of about 42 percent. In the United States, the increase in containerized maritime trade over the same period was about 14 percent, rising to 48.4 million TEUs in 2018. Trucks transport most containers moving to or from seaports. While there are many seaports in the United States, the top three (Los Angeles, Long Beach, and New York/New Jersey) moved about 51 percent of the total maritime containers in 2018 [16]. In 2010 the top three seaports moved 46 percent of the total, and in 1998 they moved 38 percent. This indicates that while volume increased it was also consolidated into fewer ports. The top 10 container seaports in the United States moved about 87 percent of the total. Eight of these 10 seaports are located in metropolitan areas that, in terms of population size, rate in the top 10 percent of those in the United States [17]. Maintaining air quality in these large metropolitan areas is a continual challenge.

While the container trade has consolidated into fewer ports, the size of the containerships themselves has greatly increased. This in turn has resulted in larger surges in container handling operations, hence surges in truck traffic. The terminals themselves, while handling more containers, are generally unable to grow in size because they are located in major population centers. They have turned to pressuring cargo owners to pick up their containers faster by reducing the number of days a container can sit on the terminal (free days) before incurring a fee (demurrage). This downward trend in free days and increase in demurrage has increased the impact of these surges [18].

Truck traffic congestion at seaport terminals is exacerbated by the overall increase in truck vehicle miles traveled, which is expected to grow by 52 percent—from 397 billion miles in 2018 to 601 billion miles in 2050 [19].

Growth in port traffic causes a direct strain on fixed infrastructure capacity, such as port access roadways and terminal gates. Increasing vessel sizes strains landside operations by exacerbating peaks in loading and offloading, due to peaks in truck arrivals for container delivery or pickup. Other strains on container terminals include sporadic operational issues, such as surges in import volumes, terminal staffing problems, cargo surges, and weather events. This section discusses some of these factors, their causes, and trends.

To better manage congestion, many terminals, and nearly all terminals in large ports, have adopted truck appointment systems (TAS). “The TAS is a practical way for the transport company (forwarder) and the terminal operator to communicate…In a traditional TAS, the terminal operator pre-sets the maximum number of trucks that can arrive at the gate for each time window, and the transport company (forwarder) books appropriately so as not to exceed the maximum number of trucks per time window. The terminal operator then rejects reservations for trucks from transport companies (forwarders) that exceed the maximum number of trucks per time window (4). The traditional TAS allows the terminal operator to control the truck congestion between the gate and the yard by limiting the maximum number of truck arrivals” [20].

The APM Terminal in Mobile, selected for this project, operates a TAS and requires drivers to make appointments.

For drayage truck drivers, daily success is based on the number of round trips (shuttling a container to or from a container terminal to a local destination) they can complete, since most drivers are paid a flat fee per trip (fee will be based on destination). Because the distance involved with drayage varies by destination, terminal turn time is the one metric that can be compared across the board. Terminal turn time gauges drayage efficiency and represents the time need to enter a container terminal, pick up and/or drop off a container, and depart a container terminal. Terminal turn times can be measured in the following two ways:

- The container terminal begins recording turn times when the drayage driver arrives at the entrance gate and ends recording when the driver leaves the exit gate. These reported turn times range from a minimum of about 10 minutes for a completed simple transaction to as much as 90–100 minutes.
- Overall turn time experienced by drayage drivers, however, includes queuing time before drivers reach the terminal gate itself. The additional time spent waiting outside the entrance gate has been reported in various surveys to be as long as 2 hours. The study team observed waiting times ranging from zero hours (i.e., when there was no queue) to 4 hours or more when terminal operations were severely disrupted [10].

The APM Terminal selected for this project tracks truck turn times using the second method described above. As shown in Original photo © Google® Earth™. Arrows and text added by report authors, 2022. [3] [21]

Figure 7, when the trucks turn into the terminal they pass through an OCR portal (OCR barn) before they queue to be processed at the entry gate. Total turn time (time truck enters until it leaves the terminal) averages 51 minutes (normal range of 45–65 minutes depending on day of the week and other factors).

Original photo © Google® Earth™. Arrows and text added by report authors, 2022. [3] [21]

Figure 7. Photograph. APM Terminal Mobile truck gates.

Trucks queuing for excessive periods of time at the entrance gates to other container terminals is a symptom of congestion within the terminal, rather than an indication that the gates are causing congestion. The exception to this conclusion can occur at terminals where trucks are allowed to queue before the terminal opens its gates and that terminal allows trucks without appointments to enter. The gates do throttle truck flow so that efficient loading and unloading of containers to and from the ships and onto the chassis can take place in the terminal. The gates themselves are efficient operations and while a truck attempting to enter a terminal gate without proper documentation can create a short delay, most container terminals maintain a trouble lane in which the offending trucks will wait and not block traffic until the issue can be corrected. If the issue cannot be quickly corrected, the offending trucks will be directed to use the turnaround lane and depart the terminal.

While there have been improvements in managing truck congestion at container terminals, congestion remains a challenge and it is easily exacerbated by sudden changes in shipping patterns. Currently the Nation is experiencing a massive inflow of imported goods compared to outgoing goods, which has created a massive stockpile of empty containers that, in turn, are causing long waits for truckers wanting to enter a container terminal [22]. In some cases, terminals are restricting the flow of empty containers being returned to the terminals or requiring them to be delivered to alternate temporary storage locations away from the terminal [23].

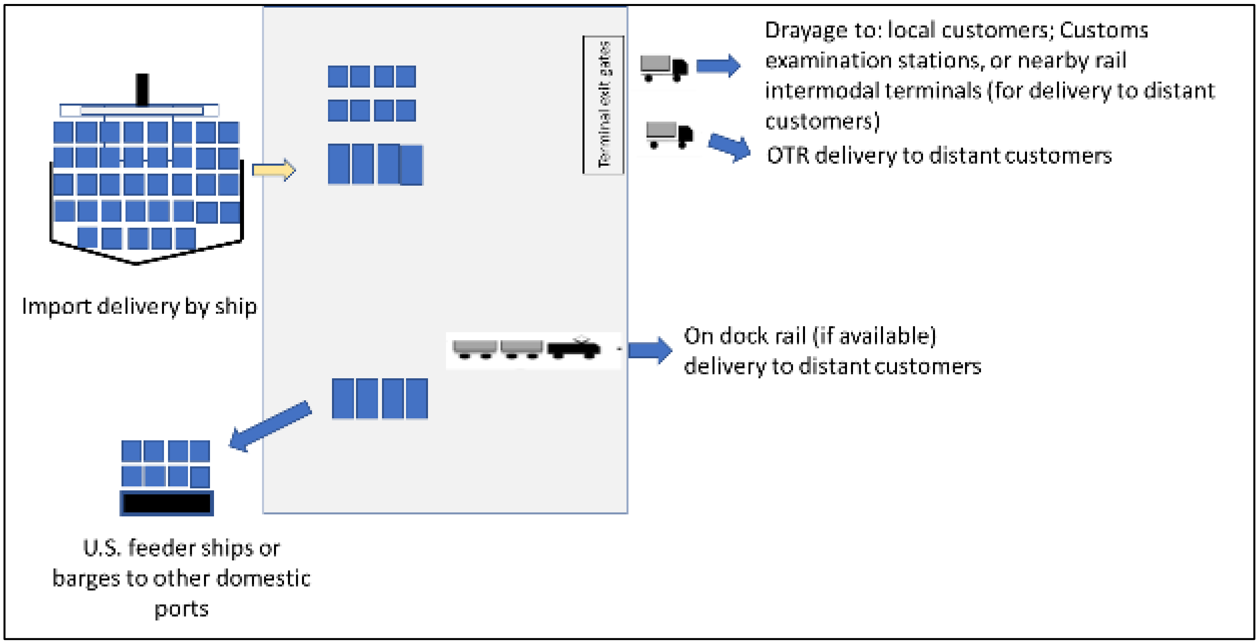
Drayage operators are also taking steps to reduce the time they spend waiting on lines by buying or long-term leasing container chassis so that they do not need to wait on lines at the chassis pool locations. Some operations are also working to adopt a process referred to as triangulation. With triangulation, rather than a dray driver returning an empty container (after it has been unloaded by an importer) to the container terminal, the container is delivered to an exporter to be loaded. This practice is known as a street turn.

Lastly, in some of the larger ports, certain container terminals are using a peel-off program to reduce truck turn times. “With peel-off, containers belonging to participating cargo owners and trucking companies are pre-positioned in separate stacks in the marine terminal after discharge from the vessel. The user’s designated motor carrier(s) take(s) delivery from the grouped containers on a last-in, first-out basis–“peeling” the containers off from the top of the stack” [24]. This reduces the number of times a container needs to be moved after it is placed in a stack to one rather than the normal average of three.

Short-Haul Drayage Automation

Drayage is an important part of maritime supply chains and often accounts for a high percentage of overall transportation costs and a large proportion of truck arrivals at container terminals. Port drayage is defined generally by those in the shipping industry as “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” [25]. This general definition has been refined by the project team to read, “Port drayage is the pickup or delivery of containers by truck to a container terminal in which both the trip origin and destination are in the same geographic region”. All short-distance truck transport of containers to or from the port—no matter if import, export, or transshipment container—are considered port drayage. The following processes are important to understand:

- Import containers, either full or empty, are brought to a container terminal by ocean carriers (container ships). Containers unloaded from the ship will either be transported to their receiving parties by truck or rail or will be moved by another vessel (ship or barge) to a port closer to their receiving parties (transshipped), as shown in Source: FHWA, 2022.
- Figure 8. Foreign ships may move empty containers to another U.S. port. Loaded containers, however, can only be transported from one port on the United States to another by U.S. flagged vessels; this is infrequent because most containers are moved by rail or truck after they are discharged from a container ship [26].
- Import containers that are not being transshipped will be transported to destination by truck or rail or a combination of both. If the distance involved is relatively short, trucks operating in the truck drayage sector will be used. If the distance involved is significant, trucks operating in the OTR trucking sector will be used. If rail will be used and the container terminal has actual on dock rail, the containers will be loaded onto the rail cars using container terminal equipment. If the there is no actual on dock rail and there is a rail intermodal terminal located nearby, the containers may be transported by truck drayage to the rail terminal.



Source: FHWA, 2022.

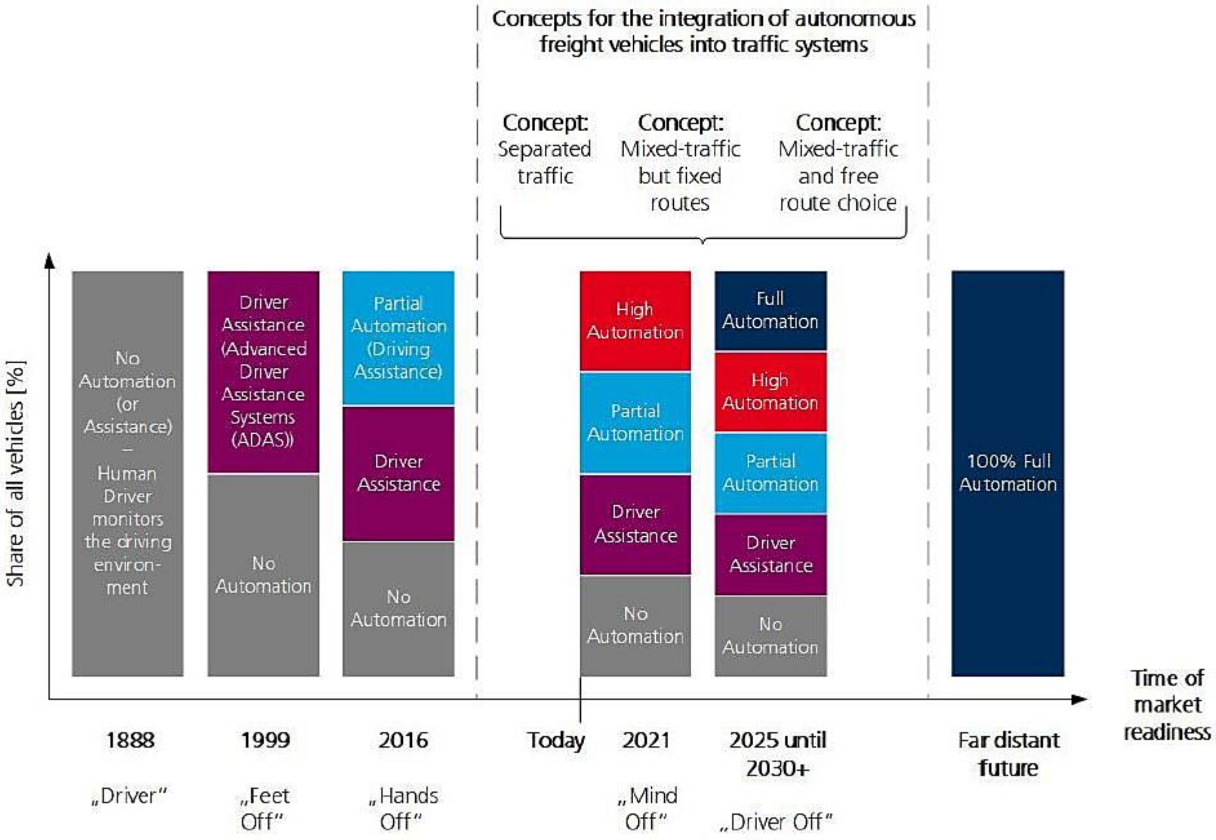
Figure 8. Diagram. Drayage as part of the import transport chain.

The main focus of the proposed concept is actions at the terminal gate, related yard operation, and drayage transportation. The autonomous trucks will connect with a container terminal's TAS to arrange an appointment time. The vehicle will electronically convey the proper documents to the terminal gate necessary for entry. At the gate, the vehicle will stop for a security inspection. It will receive information about the container loading and unloading locations it needs to transit to, as well as terminal traffic data. The truck will navigate to the specified locations, drop off and/or pick up a container, and begin its departure by passing through the RMP (and secondary inspection if it fails) and stopping at the exit gate for a security check. The truck will the travel to the rail intermodal yard, where it will provide the necessary documentation to enter and will drop off and/or pick up a container at the specified location before returning to the container terminal. CARMA Cloud could manage the rules of this fleet as it drives through each of the activities.

Nature of Changes

The move toward automation of container terminal processes is motivated by the potential for improved reliability, efficiency, consistency, predictability, and safety as well as reduced cost of operations. Reduced environmental impact may also be a motivating factor, particularly with automation that would alleviate truck congestion. Source: Feidler et al. 2019. [27]

Figure 9 illustrates the transition to fully autonomous driving on ports.



Source: Feidler et al. 2019. [27]

Figure 9. Bar Chart. Future prospects of autonomous driving in ports.

Source: Feidler et al. 2019. [27]

Figure 9 envisions three concepts of implementation of automated road transport within port facilities:

- **Separated traffic:** Examples of this concept are operation of automated shuttles in factories and theme parks. Advantages of this use case would include low-complexity requirements in the autonomous vehicle and roadway environment, and higher safety due to minimal or no interaction with other vehicles and pedestrians. In cases where physical separation is used between autonomous vehicles, rights-of-way, and mixed-traffic infrastructure, the benefits of this approach may be further enhanced. Further, the speed of vehicles and consequently the capacity of the right-of-way may improve due to minimal unplanned stoppages, since other (manual) vehicles or pedestrians are setting the speed. Vehicle-to-vehicle and vehicle-to-infrastructure communication would be supporting technology, not a prerequisite in this scenario [27]. The disadvantages include the need for additional space for exclusive lanes and cost for new construction such as barriers and other traffic facilities. Further, intersections between autonomous and human-driven vehicles can be complicated to manage.
- **Mixed traffic but fixed routes:** Most recent deployments of autonomous shuttles are mixed with some traffic, such as pedestrians or other human-driven vehicles [28]. A fixed route provides a semi-controlled environment that would largely depend on predictable vehicle maneuvers; such a concept could be implemented with vehicles having less than SAE Level 5 automation. The fixed route could

include use cases involving movement of autonomous vehicles within one port, such as between two terminals, between two port facilities, or, as in the proposed use case, between an off-site control handover point and the port terminal.

- **Mixed traffic and free-route choice:** Since this concept involves the autonomous vehicle performing all tasks under all conditions and situations, it could only be applied with SAE Level 5 automation. It would also place additional requirements on the communications and physical infrastructure.

Terminal Operations

Automated horizontal transport for short-haul drayage requires coordination with several manual and non-manual operations. To support the proposed concept of short-haul drayage using an automated truck, the following considerations apply:

- **Interaction at the rail intermodal yard:** A limited inspection function is expected to take place at the rail intermodal yard. Optical character recognition (OCR) is currently used at the gates of many terminals to automatically identify a container by its unique reference number, and often to identify the truck by its license plate. OCR eliminates the need for personnel to manually perform this task. This identification for containers can also be used at the rail intermodal yard. Other checks relevant to export containers that may take place at this point are seal status, door direction, and container damage. Manual intervention may be required for exception handling only, when numbers are difficult to interpret or when the terminal operating software (TOS) rejects the container being handled.
- **Interaction at the yard gate:** The first interaction of the automated truck with the port facility is arranging an appointment via the terminal’s TAS. The truck will then proceed to the container terminal’s truck entry gate. For the truck to enter the facility, the paperwork (actual or electronic) pertaining to the cargo, truck, and driver needs to be in order, and the truck cab needs to be inspected (manually or by closed-circuit television) to determine if any unauthorized personnel are in the cab. About 5 percent of trucks arriving at a container facility's gates have paperwork problems that need to be resolved before the trucks can enter, otherwise they will end up blocking space needed for operations [29]. To avoid paperwork problems, trucks in this study would not be dispatched until the facility receives confirmation that all paperwork is in order.
- **Navigation to and within the yard:** The proposed concept involves mixed traffic over a fixed route. The main requirements for the operation of an automated vehicle for this concept include:
    - Reliable positioning, perception, and navigation systems such as transponders or magnets buried in the ground and antennas in the bottom of the vehicle, global positioning system (GPS) satellite positioning (real-time-kinematic-GPS delivering centimeter-grade accuracy); local radio-positioning networks and radio frequency identification (RFID) systems; laser-based positioning; camera-based positioning; and millimeter-wave-radar positioning [29].
    - Wireless communication systems, such as dedicated short-range communication (DSRC) or fifth-generation (5G) mobile networks. These technologies enable communication of sensors and devices. Proposed measures include provision of low-latency communication methods, such as DSRC and cellular vehicle-to-everything (C-V2X), and preparation for how to handle compliance of data generated by vehicle-to-everything (V2X) infrastructures with national or international law.
- **Interaction with cranes:** In the terminal yard the truck performs or participates in the following actions, which may be fully or partly automated:
    - Park at the pickup/set-down location of containers.
    - Pickup/set-down of containers on platforms under the quay crane or transferred to other vehicles.

Automated yard cranes are typically equipped with sensors based on laser and/or infrared technologies, advanced camera imaging technologies and OCR, and crane management information systems that continuously report the status of the crane [29]. The control of sway and skew of the cranes is performed remotely. Remote operation of the crane minimizes human interaction with large machines, which reduces risks.

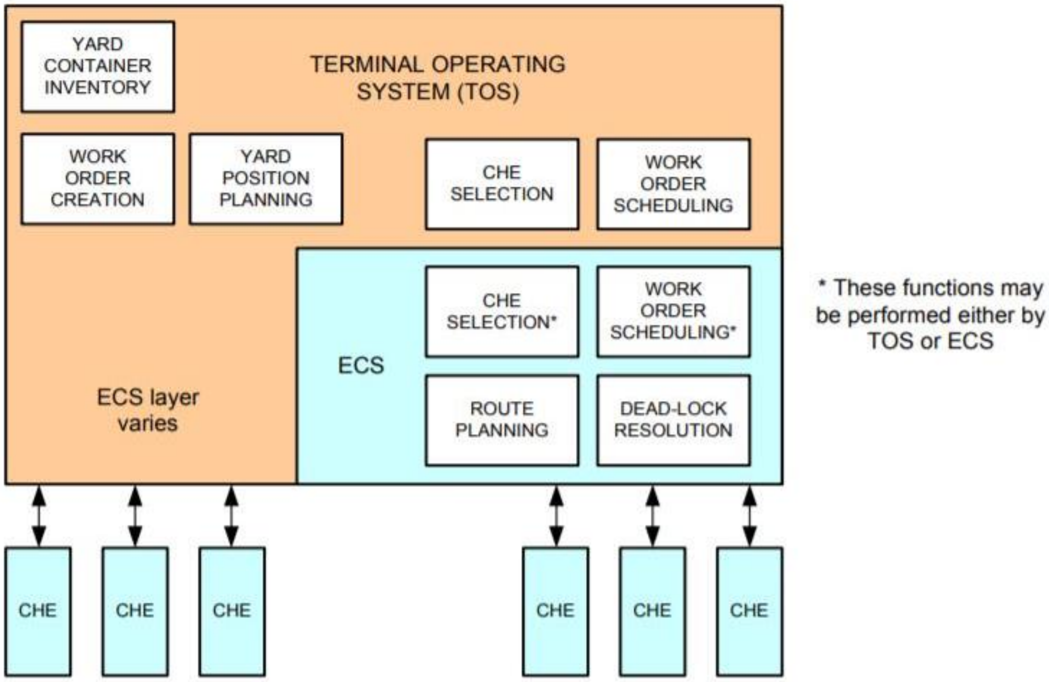
Terminal Management

In order to support automated drayage of container cargo, terminals need to move toward digitalization and upgrading or adapting physical infrastructure accordingly. The changes needed may include enhancing the quality of pavements, ensuring road markings and signage are intact, and acquiring digital networks to support communication. Key aspects of terminal management that need to be examined or updated to accommodate the proposed concept include:

- **Vehicle and container ID systems and real-time location:** While OCR is typically used on terminal facilities for loading/unloading containers and at the yard gate, equipping a container or vehicle with an RFID tag can enable checking its location at all times remotely. However, currently, equipping all containers passing through the container terminal with RFID tags is unfeasible. With the rapid development of Internet-of Things, technology that enables cellular communication may become cheaper and more widely available in the future. Using the technology described above, control systems can maintain the location information of each container and vehicle in real time. Knowledge of the exact location of vehicles and containers minimizes the risk of wrong moves and improves efficiency by minimizing travel distances, empty traveling, and waiting time [30].
- **Terminal operating system:** TOS controls the logistics of a terminal, including key functions such as vessel planning, container inventory maintenance, job order creation, and gate operations. This may be an off-the-shelf commercial product or developed by the port facilities. In order to support automated truck operation, a TOS may need to be equipped to perform:
    - Management/optimization of location of vehicles and containers. This includes yard inventory of containers and planning storage locations.
    - Management of movement. This involves maintaining an inventory of container moves via cranes; generating job orders; scheduling orders; and dispatching vehicles, containers, and cranes at the time of transport. It also involves control of gate movements of trucks, gate appointments, and transfer points.

The movement of multiple automated vehicles may be controlled by a single software module referred to as the equipment control system (ECS). PEMA defines ECS as “the software that monitors and controls all events and processes at equipment level, either for a single container handling equipment (CHE) or group of CHE” [30]. Source: PEMA, Container Terminal Automation, 2016. [30]

Figure 10 **Error! Reference source not found.**illustrates the concept of the relation and interaction between a TOS and an ECS.



Source: PEMA, Container Terminal Automation, 2016. [30]

Figure 10. Diagram. Terminal operating system and equipment control system.

Chapter 4. Proposed Concept

Background, Objectives, and Scope

Automation and semi-automated support systems are not new to terminal operations—the movement of containers throughout terminals and onto trucks has become increasingly automated over the past few decades. However, automated systems have largely proliferated in centralized machine and conveyance operations rather than drayage operations. Drayage operations are decentralized and distributed among smaller operators using a fleet of trucks, that while compatible with containers, have varying ages and mechanical conditions. This proposed system assumes compatibility with the existing structure while gaining efficiencies associated with automating drayage tasks within the terminal.

Terminal Capabilities

This ConOps relies on existing centralized systems available in terminals used for tracking or logging the movement of containers from ships; to the storage yard; and onward to trucks, trains, or other ships outside of the port. These systems may be simplified to two components: 1) a back-end database about the physical location, timelines of movement, ownership, origins, and destinations of containers and 2) a front-end system to communicate relevant information to querying stakeholders, specifically terminal operators, shippers, brokers, customs officers, and other individuals or organizations interacting with the container terminal operations. Back-end databases of container data are robust and built out, and in this proposed system assumed to remain unchanged. Terminals must adjust the front-end system to be compatible with vehicles operating within the terminal. The terminal must provide up-to-date control and location data to the vehicles at a rate that avoids collisions or frequent rerouting. These data should include:

- Origin, destination, content, and ownership data of relevant containers.
- Weight and loading patterns of containers.
- Relevant mapping and terminal layout data, updated immediately following any change.
- Crane locations and status of container operations.
- Locations of CHE and status of operations.

As systems are further developed, more information may also be necessary. Any front-end data system should be flexible and extendable to other data as future needs arise.

A terminal in this scenario should also have a robust communications infrastructure. Existing terminal operations often include manual transmission of information with low throughput that is subject to propagation delays. In a future automated terminal, it may be that terminal-mapping and agent status information propagation delays are safety risks. The terminals in this concept assume a robust, high-throughput data transmission infrastructure comprised of high-bandwidth links to both terminal-controlled infrastructure and agents within the system. At present, this is assumed to be short-range communication (e.g., DSRC), but in the future may be another technology (e.g., 5G data broadcasts).

Automated Truck Capabilities

The trucks in this automated terminal environment must move around the terminal in a way that promotes efficiency and protects the safety of workers and cargo. They must also be compatible with existing infrastructure both inside and outside the terminal. This compatibility needs to include an ability of the truck to communicate with mobile terminal equipment in order to better manage traffic congestion within the terminal. As a result, it is assumed the general dimensions and mechanical systems of a truck in this concept will generally remain unchanged. In order for any vehicle within the system to operate as designed, the agents (trucks) within the system must maintain fundamental communication and mechanical operation. What must be upgraded, then, are automated control systems and the communications systems.

Automated Control Systems

For the purpose of this ConOps, it is not beneficial to specify requirements for truck automated control systems; instead, the focus is on the functionality necessary for operation within the terminal. The automated control systems must have several capabilities. The first is system health monitoring. Where the operator of a manually operated truck can monitor mechanical problems (through sounds, feel, etc.), an automated truck must be able to monitor faults and report them to a fleet manager when they require coming to a stop. Second, the system must be capable of identifying the physical characteristics of the operating environment. A truck moving through a physical system must be capable of identifying moving and static hazards (e.g., person walking across the yard, or a stack of containers) and maintaining a map of those operating environment features. Third, the truck must be able to control its power and trajectory within the context of its operating envelope. This includes control of the ignition to reduce idling. Where smaller vehicles may need only trajectory control, a truck with a trailer must integrate changes in its operating envelope associated with turns to avoid collisions with operating environment features. Fourth, the automated control systems must be capable of integrating inputs from health monitoring, environmental mapping, and mechanical control to conduct efficient path planning through the system that avoids potential future physical conflicts.

Communications Systems

Just as truck operators and terminal operators must now speak the same language to convey information, automated trucks and terminal control systems must use the same interfaces and data formats to operate efficiently. An automated truck moving through a terminal requires the ability to take direction from the central terminal control system, and also communicate and receive intentions from other agents moving throughout the terminal. Specifically, the truck must be able to accept location data and routing instructions for a place to wait for loading and unloading by a crane, and then accept location and routing to exit the port. The truck must also be able transmit and receive status information to the terminal and to other agents and mobile terminal equipment moving throughout the terminal. This is assumed to be short-range communication (e.g., DSRC), but in the future may be another technology (e.g., 5G data broadcasts).

While wireless communication would be key for the automated vehicle to successfully perform the drayage operations described, it will share the environment with other non-connected and non-automated vehicles and users. Many times drivers are able to communicate intentions using exterior lighting, hand gestures, or even a glance. To safely operate in this environment, the automated truck should have an equivalent means of communicating with non-connected and non-automated users. Typical indicators, such as brake lights and turn signals, should be used. Additional indicators that show the vehicle is in driving mode, show the future state of the vehicle, and that replace eye contact should be considered. The following are examples of potential communication methods with non-connected and non-automated users:

- Audible signals to indicate to pedestrians that they have been detected.
- A light strip around the vehicle.
- Textual messages to indicate intent.
- Projection onto the road surface of future vehicle path.

Operational Movements

A number of operational movements can be conducted between container terminals, cargo consignees/consignors, intermodal rail terminals, other container terminals, Government (primarily CBP) examination stations, empty container depots, and chassis pools. This project focuses only on the movement of containers (full and empty) between the container terminal and the rail intermodal terminal. Each movement is defined by the change in physical space, and necessary data flows and other requirements are described. These steps are further differentiated by drop-off and pickup processes.

Rail Intermodal Yard to Terminal Entry Gate

When the truck receives an appointment to enter the container terminal, the central terminal control system broadcasts directions for the automated truck to proceed to the terminal gate for necessary inspections and intake. The terminal system can broadcast either a series of waypoints for the truck to follow, or the location of the gate and require the truck to determine its own route. The truck then proceeds to the gate and undergoes security inspections. The central terminal control system then updates its database with acquired information about the truck and the container’s (if applicable) entry. Original photo © Google® Earth™, 2021. Line and text boxes added by report authors. [3] [31]

Figure 11 shows the route from the rail intermodal yard to the terminal entry gate.

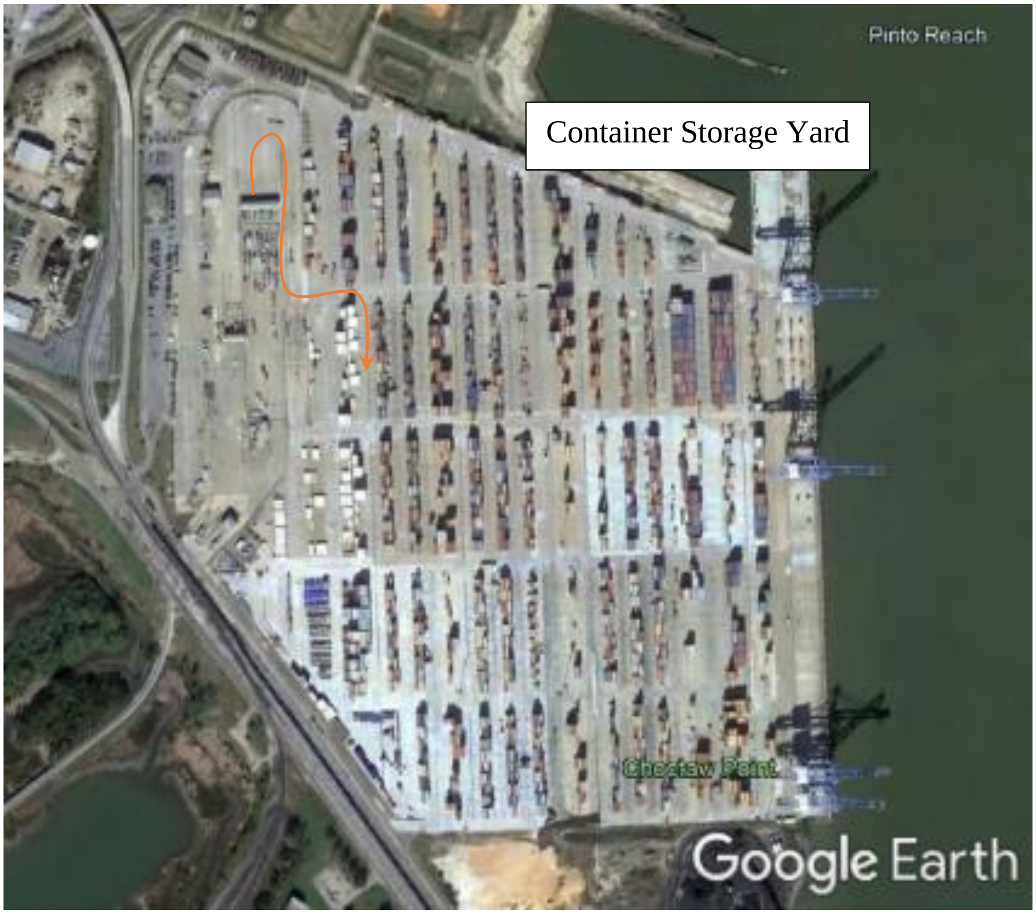
Original photo © Google® Earth™, 2021. Line and text boxes added by report authors. [3] [31]

Figure 11. Photograph. Route from rail intermodal yard to terminal entry gate.

Terminal Entry Gate to the Container Storage Yard

When the truck arrives at the terminal entry gate, information about container offloading and/or container loading locations and traffic conditions on the terminal is uploaded to the central terminal control system. The central terminal control system then broadcasts routing and exit information to the truck, and the truck moves on its own throughout the terminal to the location. At this point, the truck holds until a mobile container handling unit lifts the container off the truck and proceeds to a container loading location (if applicable). Both the truck and CHE transmit data about the loading status of the container, and when they concur the container is no longer on the truck, the truck departs or moves to a location to receive another container. Original photo © Google® Earth™, 2021. Line and text boxes added by report authors. [3] [32]

Figure 12 shows the route from the terminal entry gate to the container pickup location in the container storage yard.



Original photo © Google® Earth™, 2021. Line and text boxes added by report authors. [3] [32]

Figure 12. Photograph. Route from terminal entry gate to container pickup location in container storage yard.

Container Storage Yard to Radiation Portal Monitor

If the truck is transporting a container, the central terminal control system broadcasts routing information to the truck, directing it to stop at the RPM. If the central terminal control system receives a message that the RPM detected elevated levels of radiation from the container, it will direct the truck to stop at a specified location in the terminal for secondary inspection. The container will then undergo inspection before the truck is cleared to proceed out of the gate. The central terminal control system then updates its database with information about the container based on the results of the inspections. Original photo © Google® Earth.™, 2021. Line and text boxes added by report authors. [3] [33]

Figure 13 shows the route from the container pickup location to the radiation portal monitor and the terminal exit gate.

Original photo © Google® Earth.™, 2021. Line and text boxes added by report authors. [3] [33]

Figure 13. Photograph. Route from container pickup location to radiation portal monitor and terminal exit gate.

Terminal Exit Gate to Rail Intermodal Terminal

Trucks without containers and trucks with containers that have been cleared by the RPM will follow routing information they had received upon entering the terminal to the terminal exit, and then proceed back to the rail intermodal terminal area to drop off and/or pick up another container. Original photo © Google® Earth.™, 2021. Line and text boxes added by report authors. [3] [34]

Figure 14 shows the route from the terminal exit gate to the rail intermodal terminal.

Original photo © Google® Earth.™, 2021. Line and text boxes added by report authors. [3] [34]

Figure 14. Photograph. Route from terminal exit gate to rail intermodal terminal.

Rail Intermodal Terminal

Trucks arriving at the rail intermodal terminal will move to the control handover point to drop off or pick up a container. Upon entry, the central terminal control system broadcasts routing and exit information to the truck, and the truck moves on its own through the terminal to the location. At this point, the truck holds until a mobile container handling unit lifts the container off the truck and proceeds to a container loading location (if applicable). Both the truck and CHE transmit data regarding the loading status of the container, and when they concur the container is no longer on the truck, the truck departs or moves to a location to receive another container. Original photo © Google® Earth.™, 2021. Line and text boxes added by report authors. [3] [35]

Figure 15 shows the route within the rail intermodal terminal.

Original photo © Google® Earth.™, 2021. Line and text boxes added by report authors. [3] [35]

Figure 15. Photograph. Route within the rail intermodal terminal.

Demonstration

Potential means of demonstration for this concept are described in this section. A demonstration in partnership with an operational port is the preferred means to showcase the proof of concept. This would be preceded by a proof-of-concept demonstration using a scaled-down environment based on the partner port. Both demonstrations would follow the operational movements described in the *Operational Movements* section using vehicles equipped with CARMA Platform and infrastructure elements equipped with CARMA Cloud.

Scale Demonstration

CARMA 1tenth has been developed to encourage widespread adoption of cooperative vehicle technology. CARMA 1tenth is a vehicle hardware platform scaled down to one-tenth the size of a standard passenger vehicle. The 1tenth vehicle is equipped with a suite of sensors intended to replicate those that are most important to a full-size automated vehicle. These sensors include a light detection and ranging unit, GPS, V2X radio, camera, and computer. The 1tenth system includes a version of CARMA Platform that is tailored to run on hardware with limited resources.

The CARMA 1tenth truck will be used as a tool to demonstrate the proof-of-concept drayage application. The port drayage application that was developed on the full-scale trucks will be adapted for CARMA 1tenth. The vehicle itself will go through integration and validation tests to verify its performance in running the application.

To complete the demonstration, a scale model of the selected port will be developed. The model will recreate key locations of the port and control handover area, including the entry and exit gates, inspection point, and container stacks, to provide a complete picture of how the automated truck would improve operations of the port. The 1tenth truck will perform the container pickup/drop-off operation within the scale port, perform the interaction with the inspection and exit gates, and move to the scale control handover area.

The scale model will be developed at TFHRC and will be designed with portability in mind. A portable demonstration will allow the project team to provide a more interactive demonstration of the concept to a greater number of stakeholders at sites such as the USDOT headquarters, which may improve understanding and acceptance of the concept.

Full-Scale Demonstration

In cooperation with the selected port, a full-scale demonstration will be planned and executed within the port itself. The project team will work with the port to identify a control handover area, a suitable route within the port and control handover area, and a suitable route between the two. The project team will also work with the port on the following tasks:

- Creating a high-definition map for the entire route.
- Identifying a storage location for project equipment, including the automated CMV, containers, and chassis.
- Using containers and/or chassis owned by the port.
- Filming in and around the port.

After finalizing the plan for how the demonstration will proceed, a series of validation tests will be carried out using the automated CMV. The demonstration will only proceed once the tests have been successfully carried out.

Coordination between the project team and the port will be key to carry out all phases of this demonstration, beginning with access to the port, which is controlled. Test personnel will need to secure appropriate credentials to access the port, as needed, to prepare for testing and demonstration. Safety drivers who hold a commercial driver’s license will be identified to oversee the operation of the trucks and take over for any failures in the automation system. While the port is operational, other traffic may present obstacles to the operation of the automated vehicle that will need to be addressed.

Finally, while an agreement was reached with the APM Terminal to act as a model for the small-scale demonstration, the Terminal would not commit to a full-scale demonstration at their facility. While the project team would first work with APM Terminal to organize the next phase of the demonstration, if an agreement cannot be reached then the search for a port partner would be reopened. In that case, this document would be revised to address a new port partner.

Chapter 5. Requirements

The concept described in this document introduces automation to the trucks that perform typical drayage operations for a terminal in an effort to improve performance. To successfully carry out this concept, certain features and capabilities are required. The needs of the system drive these requirements, as described in the ConOps. Table 5 synthesizes a high-level set of these needs.

Table 5. Needs of the system.

ID #	Operational Need
General Needs	
CFAD-N1	Need for improved transparency and visibility of cargo data between container terminal terminals and drayage trucking firms.
CFAD-N2	Need for effective communication between drayage trucks and CHE when unloading/loading containers.
CFAD-N3	Need for effective communication between terminal operators, drayage trucks, consigners/consignees, and cargo screening operators (CBP).
CFAD-N4	Need for increased safety during interactions among humans, material handling equipment, and other road users.
CFAD-N5	Need for a low-latency wireless communication system.
CFAD-N6	Need for the capability to digitize and share documentation.
CFAD-N7	Need for a drayage truck that is capable of full autonomous driving and manual driving.
Terminal-Specific Needs	
CFAD-N8	Need to reduce the number of days a container stored in the terminal for pickup.
CFAD-N9	Need to mitigate operational impact from sporadic issues such as insufficient terminal staffing, cargo demand surges, and equipment issues.
CFAD-N10	Need for an automated truck to self-monitor and report system faults to terminal operators.
CFAD-N11	Need to minimize truck intake processing time and increase reliability at the yard gate.
CFAD-N12	Need for the TOS to be capable of managing movement of multiple automated vehicles.
CFAD-N13	Need for the automated trucks to be capable of operating within the terminal and dedicated area.
CFAD-N14	Need for the automated trucks to be capable of transit between the terminal and control handover point in mixed traffic on public roads.
Automated Truck-Specific Needs	
CFAD-N15	Need for reliable vehicle positioning, perception, and navigation systems.
CFAD-N16	Need for software module that can manage the movement of multiple automated vehicles.
CFAD-N17	Need for a physical and virtual infrastructure to facilitate optimal automated truck operation.

Source: FHWA, 2022.

The requirements of the environment in which this concept is implemented are derived from the needs.

Table 6 provides a set of high-level requirements. In any deployment, these high-level needs should be considered in forming more detailed requirements for a specific port.

Table 6. Requirements of the system.

ID #	Requirement	Need Addressed
Infrastructure Requirements		
CFAD-R1	The infrastructure must have geofenced boundaries and checkpoints.	CFAD-N4 CFAD-N15 CFAD-N16 CFAD-N17
CFAD-R2	The infrastructure must facilitate communication among actors using technologies such as DSRC, CV2X, or 5G.	CFAD-N2 through CFAD-N6 CFAD-N8 CFAD-N10 through CFAD-N17
CFAD-R3	The OCR system must be capable of identifying container reference numbers and truck license plates.	CFAD-N2 CFAD-N6 CFAD-N11
CFAD-R4	The terminal infrastructure must have high-definition environmental mapping of roadway boundaries and landmarks (e.g., lanes, signs, permanent structures) within the port.	CFAD-N4 CFAD-N13 CFAD-N15 CFAD-N17
CFAD-R5	The terminal infrastructure must have high-definition environmental mapping of roadway boundaries and landmarks (e.g., lanes, signs, permanent structures) of the control handover point and roadway to terminal gate.	CFAD-N4 CFAD-N14 CFAD-N15 CFAD-N17
CFAD-R6	The high-definition environmental mapping must be updated when changes to the roadway boundaries and landmarks (e.g., lanes, signs, permanent structures) occur.	CFAD-N4 CFAD-N13 CFAD-N14 CFAD-N15 CFAD-N17
CFAD-R7	The physical infrastructure components, such as pavement, markings, and signing, must be designed and maintained to facilitate autonomous trucks.	CFAD-N4 CFAD-N15 CFAD-N17
CFAD-R8	The infrastructure must facilitate automated vehicle operation within and between the terminal and control handover area.	CFAD-N2 through CFAD-N5 CFAD-N13 through CFAD-N15 CFAD-N17
CFAD-R15	The container transfer between the manually driven shipping truck and automated drayage truck must occur at the control handover area.	CFAD-N9 CFAD-N11
Terminal Management System Requirements		
CFAD-R9	The TOS must be capable of real-time location monitoring of container movement.	CFAD-N2 CFAD-N3 CFAD-N8 CFAD-N9
CFAD-R10	The TOS must be capable of monitoring and controlling all events and processes at the equipment level through an equipment control system module.	CFAD-N4 CFAD-N8 CFAD-N9

		CFAD-N11 through CFAD-N14 CFAD-N16

ID #	Requirement	Need Addressed
Terminal Management System Requirements		
CFAD-R11	The TOS must be able to provide routing commands and system status to the automated trucks and other actors.	CFAD-N3 CFAD-N4 CFAD-N10
CFAD-R12	All actors must handle digitized versions of required documentation for terminal drayage.	CFAD-N1 CFAD-N6 CFAD-N8 CFAD-N11
CFAD-R13	The TOS must be adaptable to variable cargo demand and non-reoccurring events.	CFAD-N8 CFAD-N9
CFAD-R14	The system must be capable of manual intervention when exception handling is necessary.	CFAD-N9 CFAD-N11
Vehicle Requirements		
CFAD-R16	The automated trucks must be capable of monitoring and reporting system faults, both in the automated control system and truck physical road readiness.	CFAD-N2 CFAD-N4 CFAD-N10
CFAD-R17	The automated truck must be able to perceive physical characteristics of the operating environment.	CFAD-N4 CFAD-N15
CFAD-R18	The automated truck must be able to control its power and trajectory within the context of its operating environment.	CFAD-N4 CFAD-N15
CFAD-R19	The automated truck must be capable of integrating inputs from health monitoring, environmental mapping, and mechanical control.	CFAD-N4 CFAD-N10 CFAD-N15
CFAD-R20	The automated truck must be capable of taking direction from the central terminal control system.	CFAD-N3 CFAD-N4 CFAD-N12 CFAD-N16
CFAD-R21	The automated truck must be capable of wirelessly transmitting, receiving, and negotiating intentions with other actors in the operational domain.	CFAD-N2 CFAD-N4 CFAD-N10
CFAD-R22	The automated truck must be capable of autonomous and manual operation.	CFAD-N7
CFAD-R23	The automated truck must be capable of operating on mixed used public roads between the terminal and control handover area.	CFAD-N14
CFAD-R24	The automated truck must be capable of indicating its status and intent to nearby humans and other non-connected users.	CFAD-N4

Source: FHWA, 2022.

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Figure 711, the map overlays showing the route from the rail intermodal yard to the terminal entry gate were added by the authors. The line shows the route that a truck may take to its destination.

[32] For Original photo © Google® Earth™. Arrows and text added by report authors, 2022. [3] [21]

Figure 712, the map overlays showing the route from the terminal entry gate to the container pickup location in the container storage yard were added by the authors. The line shows the route that a truck may take to its destination.

[33] For Original photo © Google® Earth™. Arrows and text added by report authors, 2022. [3] [21]

Figure 713, the map overlays showing the route from the container pickup location to the radiation portal monitor and the terminal exit gate were added by the authors. The line shows the route that a truck may take to its destination.

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[35] For Original photo © Google® Earth™. Arrows and text added by report authors, 2022. [3] [21]

Figure 715, the map overlays showing the route within the rail intermodal terminal were added by the authors. The line shows the route that a truck may take to its destination.

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