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

Concept of Operations for Proof-of-Concept Automated Port Drayage

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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 are being equipped with automation technologies, including CARMA, to enable a SAE Level 2-3 operation, furthering the research opportunities and capabilities available to FMCSA, MARAD, and the government.

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 a proof-of-concept automated port drayage use case. A detailed discussion of the required changes and associated benefits to enable the proposed concept is given. Finally, a detailed discussion of the needs and requirements to implement the proposed changes for automated port drayage operation 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

The Federal Motor Carrier Safety Administration (FMCSA) provides high-quality information to serve Government, industry, and the public in a manner that promotes public understanding. Standards and policies are used to ensure and maximize the quality, objectivity, utility, and integrity of its information. FMCSA periodically reviews quality issues and adjusts its programs and processes to ensure continuous quality improvement.

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List of Acronyms, Abbreviations, and Symbols

Acronym	Definition
3PL	third-party logistics
5G	fifth generation
ADS	automated driving system
ATCMTD	advanced transportation and congestion management technologies deployment
CAV	connected automated vehicle
CBP	U.S. Customs and Border Protection
CCTV	closed-circuit television
CHE	container handling equipment
CMV	commercial motor vehicle
ConOps	concept of operations
C-V2X	cellular vehicle-to-everything
DHS	U.S. Department of Homeland Security
DMS	drayage management system
DNDO	Domestic Nuclear Detection Office
DSRC	dedicated short-range communication
ECS	equipment control system
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
GPS	global positioning system
GVWR	gross vehicle weight rating
HHLA	Hamburger Hafen und Logistik AG
HRDO	Office of Operations Research and Development
ID	identification
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers

ISO	International Organization for Standardization
ITS	intelligent transportation system
ITS MARAD	Intelligent Transportation Systems Maritime Administration
ITS–JPO	Intelligent Transportation Systems-Joint Program Office
MARAD	Maritime Administration
OCR	optical character recognition
ODD	operation design domain
OTR	over the road
PEMA	Port Equipment Manufacturers Association
RFID	radio frequency identification
RPM	radiation portal monitor
SAE	Society of Automotive Engineers
STOL	Saxton Transportation Operations Laboratory
TAS	truck appointment system
TEU	twenty-foot equivalent unit
TOS	terminal operating software
TSMO	transportation systems management and operations
USDOT	U.S. Department of Transportation
YMS	yard management system

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 a proof-of-concept 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 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. 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 objectives are to develop future technologies for our Nation's ports, to accelerate adoption of available technologies, and to investigate the costs and benefits of using automated trucks for container drayage between marine container terminals and a point where control of the vehicle transitions from manual to automation. The project will develop and demonstrate a concept of connected vehicles and autonomous vehicle technology applications involving the 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 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. A list of requirements for implementation of the concept is provided in the *Requirements* section of this report.

Deployment Strategies

The project team plans on demonstrating the concept described in this document on a closed test track. The closed test track will be configured to resemble a scaled model of an actual terminal selected by the project team. 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. This would 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, researchers can consider a more widescale deployment.

Chapter 1. Introduction

Background

The Federal Highway Administration (FHWA) Office of Safety and Operations Research and Development (HRSO) performs transportation operations and research and development 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 each 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 [1], furthering research opportunities and capabilities available to FMCSA, MARAD, and the Government.

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. 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 container terminal environment in a multiyear project to increase efficiencies, increase safety, and decrease emissions. The project objectives are to develop future technologies for our Nation's ports, to accelerate adoption of available technologies, and to investigate the costs and benefits of automated truck movement for container drayage between marine container terminals and staging areas. The project will develop and demonstrate a concept of connected vehicles and autonomous vehicle technology applications involving the 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. The key objectives of this task are 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 drayage operations at container terminals and in the port areas. This report first documents the project team's analysis of drayage operations in existing ports and identifies where autonomous trucks could improve operations. The report next describes of a concept of operations (ConOps) for automated trucks, which was developed by the project team, and a discussion of potential benefits. The report then discusses a scenario to demonstrate the ConOps in which automated trucks will transport shipping containers between a container terminal and a control handover point [2]. Finally, this report documents a list of requirements for implementation of the concept.

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.
- 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 truck 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.

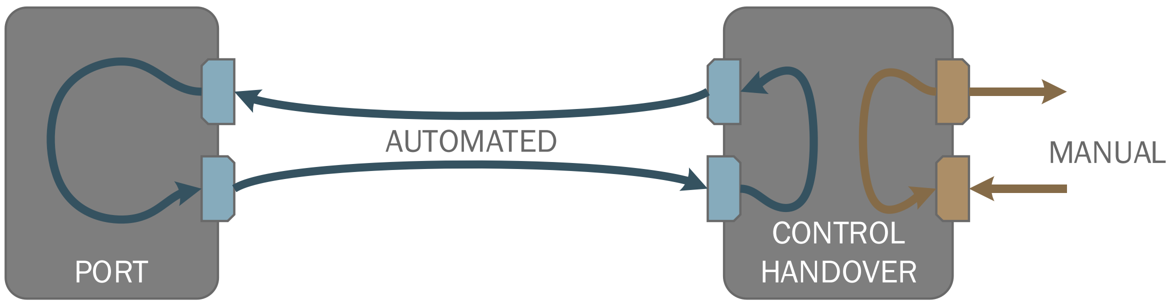
Chapter 5 provides a list of requirements for implementation of the concept.

Chapter 6 provides a list of reference documents.

System Overview

This study focuses on improving the efficiency of container terminal drayage through the use of CAVs. Container terminals are complex, and they vary in design to suit the needs of each port. While the primary goal of all ports is to move goods, factors such as location, size, and demand drive key differences in individual ports. For instance, on a wheeled facility, containers are loaded onto a chassis by the terminal operators prior to pickup, whereas in a stacked facility, containers are stored in stacks of containers and are loaded onto the chassis as part of the pickup process. Wheeled facilities have containers on chassis, which typically requires larger space, so they are more feasible at terminals with lower volumes. Some facilities stack most of their containers but maintain a wheeled section for specific customers. This is a key difference that would affect the ability to implement improvements to ports. Source: FHWA, 2021.

Figure 1 shows the flow of traffic between port and staging area in the proposed concept.



Source: FHWA, 2021.

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

The system considered in this concept uses a scenario introduced in the MARAD truck staging study involving an off-site location where automated and human-driven trucks exchanged their shipments of containers. From a technological standpoint the staging area in the MARAD study represents a point in which control of the vehicle transporting the container shifts between manual and automation (control handover point). The use of a control handover point allows the project team to focus on the ability of CAVs to operate on container terminals, including entry and departure from the terminals, rather than studying their performance over an extensive highway network. While it may be difficult to create a business case to support creation of a dedicated control handover point, most medium- and large-sized ports already contain rail intermodal terminals, trucking depots for over-the-road (OTR) trucking firms, and commercially operated trucks stops located a short distance from their container terminals that can serve the purpose of a control handover point [3]. While numerous options can serve as control handover points, rail intermodal terminals probably already have fairly advanced computerized yard management systems (YMS) that could be configured to interact with the information technology systems discussed in this document, and drayage operations to the container terminals is probably already well established [4]. The other options mentioned could be used if a computerized YMS were supplied. In this scenario, containers drayed from the control handover point by autonomous trucks will be loaded onto trucks with chassis designed to transport containers. The CAV will interface with the container terminal's truck appointment system (TAS) to obtain a gate reservation time. The truck will then transit public roads to the container terminal. The trucks will proceed to the terminal gates, waiting in queue if necessary. At the gate the truck will stop for a security inspection, conducted by terminal personnel, to ensure no unauthorized personnel are in the truck or container. This inspection may be conducted remotely by terminal security personnel through closed-circuit television (CCTV) installed at the gate. However, if the container is unsealed [5] and is listed as an empty, someone may be required to open the empty container for inspection by CCTV or a security personnel. The CAV will also electronically provide the necessary documents to the terminal's central system. The CAV will receive the location within the terminal where the container will be lifted off the chassis along with routing and traffic information (e.g., other trucks and mobile yard equipment operating within the terminal).

To translate this concept into a practical demonstration the project team made the following assumptions:

- Since the CAVs involved are incapable of hitching or unhitching to a chassis, wheeled container terminals were excluded. On stacked facilities the container handling equipment (CHE) is used to load/unload containers onto or off chassis already hitched to a truck. This project will be conducted with a stacked container terminal.

- The control handover point will be located within 10 miles of the container terminal. This is because existing automated trucks only cover a limited operational design domain (ODD), and limiting the distance limits the required ODDs. The automated trucks will operate in mixed traffic because it cannot be expected that a dedicated lane will be available to trucks performing this operation.

System Benefits

The use of automated 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 queueing times at the terminal's gates and congestion on the approach roads caused by the trucks waiting to enter the terminal. Less congestion can reduce truck turn times and emissions from idling trucks, and can improve throughput capability of container terminals. Realizing this potential will require that the automated trucks communicate with the mobile CHE (e.g., straddle carriers, stackers, and forklifts) and other trucks in the terminal either directly or through a YMS operated by the terminal operators. The automation functionality will enable the drayage truck to select the optimum route to the designated container drop-off or 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 automated 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 reduces the potential for collisions, thereby improving worker safety in 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 involves interactions among six stakeholder groups: 1) customers, 2) ocean carriers, 3) terminal operators, 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 port terminal. Movement of a customer's cargo is the fundamental reason for container 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 container 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. Goods imported may be owned by the importer or by another cargo owner.
- 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. Goods exported may be owned by the exporter or by another cargo owner.

Ocean Carriers

Ocean carriers are responsible for port-to-port marine transportation of the cargo (containers).

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 and managing drayage truck access to the terminal. 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.

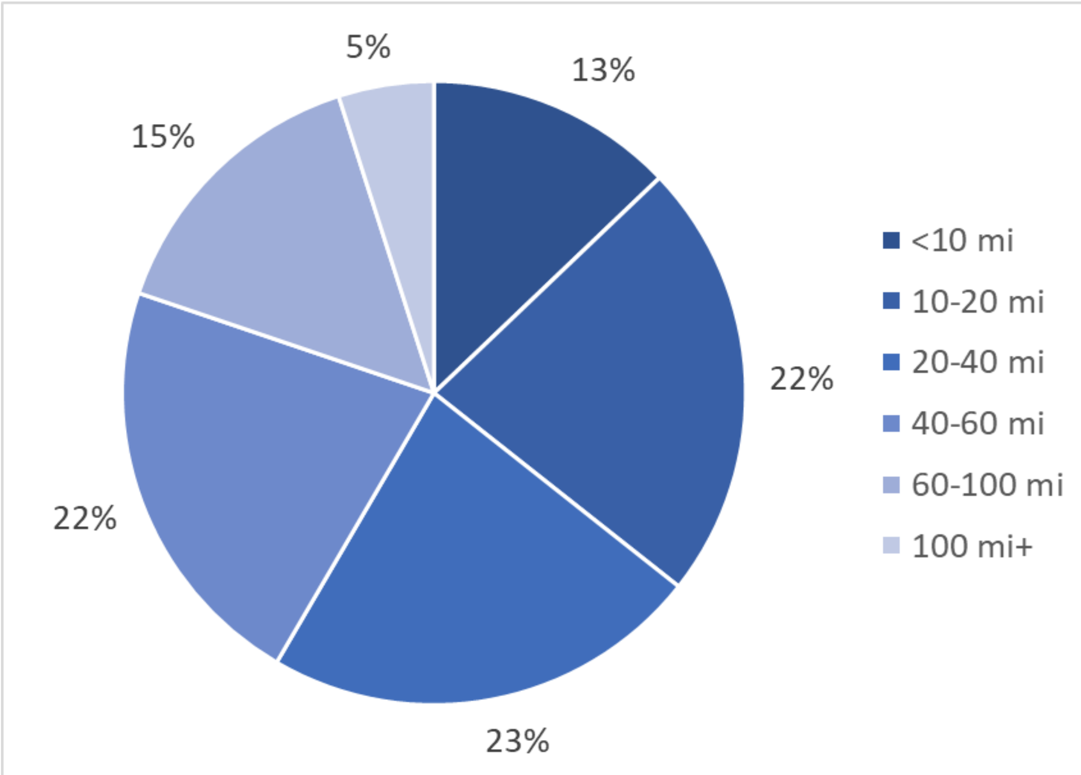
Port/Dock Workers

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, machinists, and clerks.

Trucking Firms and Integrated Service Providers

In the context of this ConOps, a trucking firm's primary responsibility is movement of containers by road. These firms are independent of the container terminal and they transport containers to or from container terminals to rail intermodal terminals, consignees, or consignors. Actors in this stakeholder group include the following:

- Drayage operators: Drayage operators of Class 8 trucks pick up or deliver containers to a container terminal in which both the trip origin and destination are in the same geographic region. The difference between a container being drayed and a container transported 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. **Error! Reference source not found.** illustrates the typical drayage distances in southern California. A National Cooperative Freight Research Program Project [6] reported 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.
- OTR operators: OTR operators drive Class 8 trucks hauling containers. The main difference between OTR and drayage operators is the distance the operator hauls the container. OTR operators generally travel 500 miles or more per day.
- 3PLs: 3PLsare contracted by the cargo owners to arrange or provide transportation of goods. 3PLs may also arrange or provide warehousing of the cargo owner's goods.



Source: Adapted from Calstart, 2013.

Figure 2. Pie Chart. Typical drayage distances for the Ports of Los Angeles and Long Beach. [7]

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 radiation portal monitors (RPM).
- **FMCSA:** primary mission is reducing 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 control handover point.
- **MARAD:** primarily focused on operations on the Nation's waters. Drayage operations provide a key interface between sea and land—drayage trucks enter the port to retrieve containers destined for inland consumers and deposit containers destined for overseas consumers. MARAD has a key interest in the movement of those containers around the ports and terminals.

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 Organization for Standardization Containers

International Organization for Standardization (ISO) containers are stackable intermodal containers suitable for shipment by ship, rail, or truck. Containers are generally 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 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

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 are designed to 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 can 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 or all-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 have it transported 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 generally involved. Legal jurisdiction of the stakeholders listed in table 1 may overlap or extend beyond the defined areas (e.g., Federal agency jurisdiction often extends beyond the terminal gates and local agencies may have authority within the terminals).

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.

Port Drayage Transactions

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

Table 2. Entry and exit transaction types.

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

Source: Tioga Group, 2011.

Drayage Processes

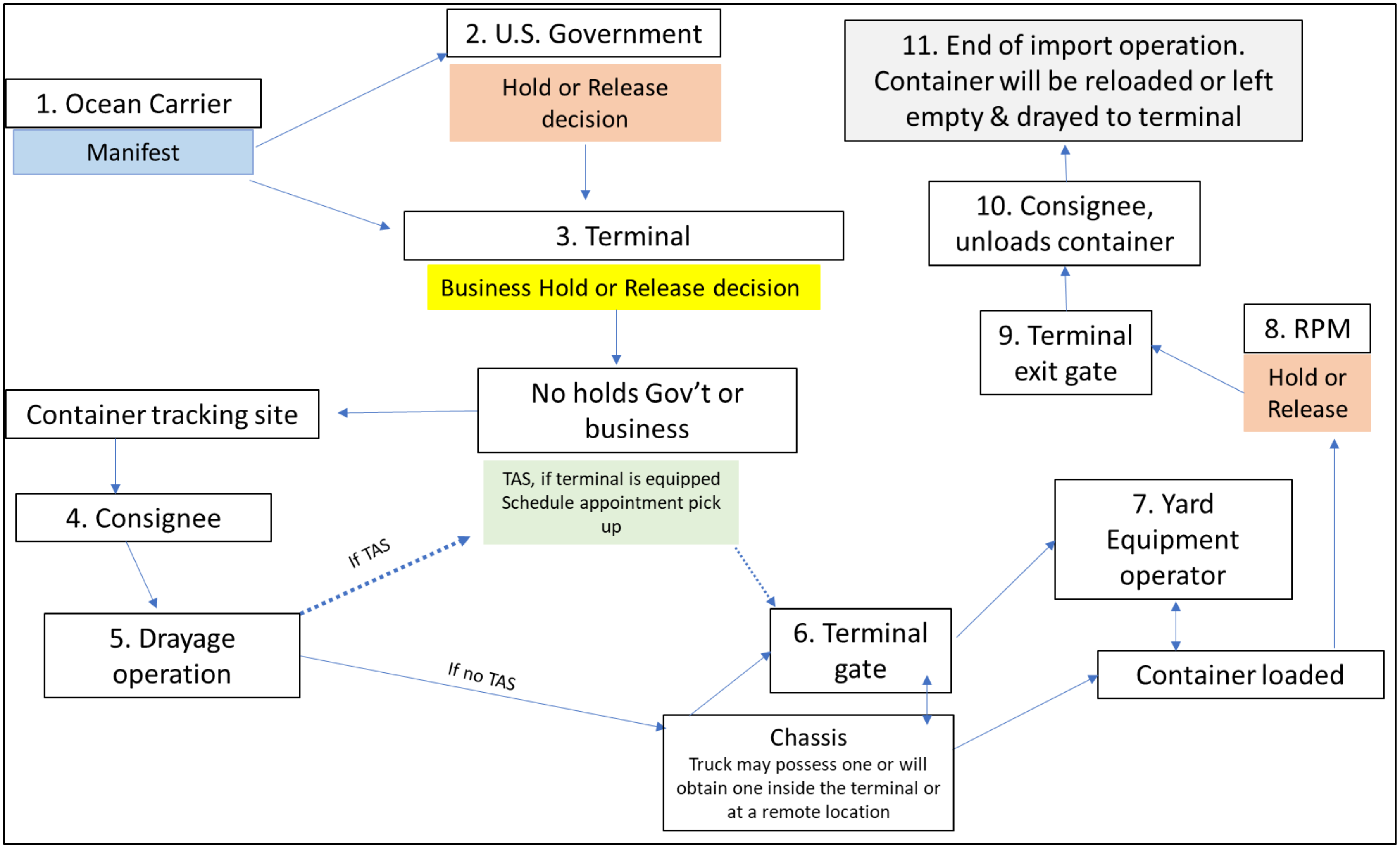
Within the scope of this ConOps, drayage consists of two main processes and one sub-process. The two main processes are import drayage and export drayage; the sub-process is the CBP container checkpoint.

Import Drayage Process

As shown in figure 3, there are 11 steps in the import drayage process, with five stakeholders involved: the ocean carrier, drayage firm, terminal, consignee, and the Government.

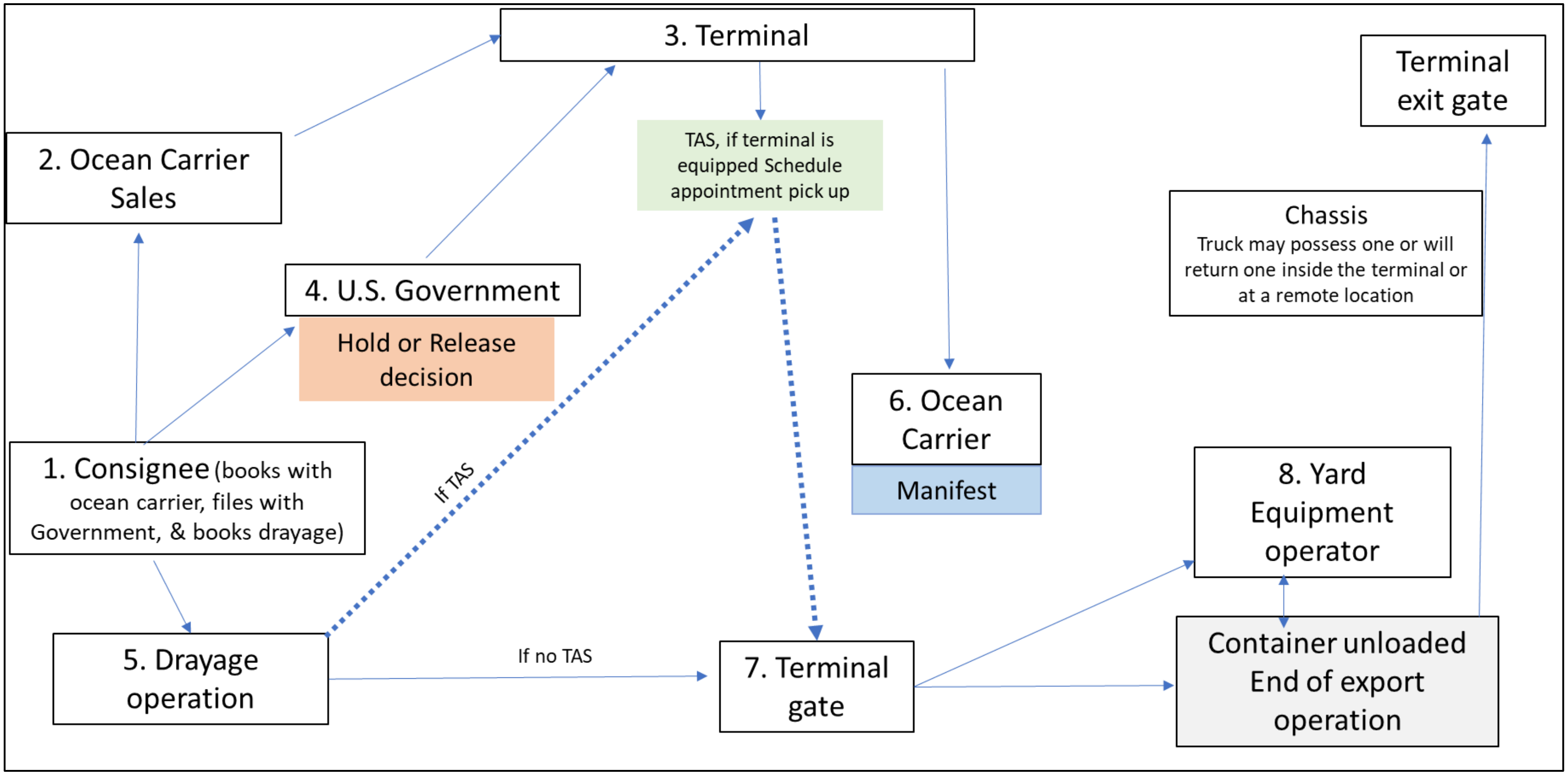
Export Drayage Process

As shown in figure 4, there 10 steps in the export drayage process, with five stakeholders: the shipper, ocean carrier, drayage firm, terminal, and the Government. Consignees are irrelevant because they are only involved in receiving goods.



Source: FHWA, 2022.

Figure 3. Diagram. Import drayage process.



Source: FHWA, 2022.

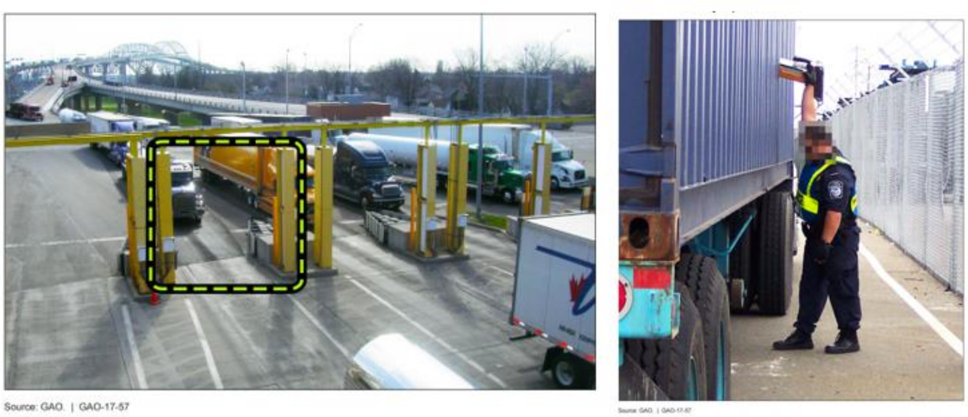
Figure 4. Diagram. Export drayage process.

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 retrieve the container [10].

RPM is a non-intrusive means of detecting elevated levels of radiation. During RPM processing, a truck with a container will drive through the RPM portal, 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 inspection area for further inspection and clearance by a CBP officer using a handheld radiation detector that can identify the source of the radiation" [11] (see Source: Government Accountability Office, 2016.

Figure 5). 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: Government Accountability Office, 2016.

Figure 5. 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 terminal, 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” [12]. 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 [13]. 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 twenty-foot equivalent units (TEU) (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 [14]. 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 consolidating 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 in metropolitan areas that, in terms of population size, rate in the top 10 percent of those in the United States [15] (U.S. Census Bureau 2019). Maintaining air quality in these large metropolitan areas is a continual challenge.

While the container trade is consolidating 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 [16].

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 [17].

Growth in port traffic causes a direct strain on fixed infrastructure capacity, such as port access roadways and terminal gates. Increasing vessel sizes strains on 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 a 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. 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” [18].

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 times is the one metric that can be compared across the board. Terminal turn time gauges drayage efficiency and represents the time needed 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 time 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 [19].

Recurring Truck Congestion

The primary reason for recurring congestion is because truck traffic is tied to container movements into and out of port facilities, and thus is directly impacted by growth in cargo traffic. Table 3 provides container throughput and truck movement data for two small-sized ports with container terminals, two-medium sized ports with container terminals, and three large ports with container terminals.

Table 3 provides the number and percentages of inbound (normally imports), outbound (normally exports), and empty containers moving through these small, medium, and large ports. These volumes are reported in TEUs. It also separates the containers moved via railroad lines extending onto terminals from those moved a short distance by trucks. The remaining TEUs are divided by 1.8 to determine how many truck movements will be necessary [20]. The table further equates the number of truck movements needed per crane per year and equates the number of truck movements needed per ship.

Table 4 separates annual truck moves attributable to inbound, outbound, and empty containers, and estimates the annual average number of trucks needed to move containers per ship. The table also shows the number of containers per day that need to be processed at the truck gates, and the inbound, outbound, and empty containers moved per hour by trucks (assuming a 10-hour gate availability). These data do not address feeder or transshipped containers (containers dropped in a container terminal by one ship that will be loaded on another ship without the container leaving the terminal).

Table 3. Annual container and truck movements at seven U.S. ports of small, medium, and large sizes.

Port	Size	Inbound TEUs (2017)	Outbound TEUs (2017)	Empties TEUs (2017)	Total TEUs (2017)	Annual % TEUs Moved by on-Dock Rail*	Annual TEUs Moved by Truck*	Annual # Truck Movements (@ 1.8 TEU per Move)	No. Cranes	Annual Truck Movements per Crane**	Annual No. Ships	Annual Truck Movements per Ship
Anchorage	S	245,000	41,000	175,000	461,000	0	461,000	256,111	3	85,370	106	2,416
Philadelphia	S	268,000	277,000	0	545,000	0	545,000	302,778	7	43,254	404	749
Baltimore	M	474,000	241,000	248,000	963,000	0	963,000	535,000	15	35,667	410	1,305
Jacksonville	M	294,000	436,000	378,000	1,108,000	2	1,085,840	603,244	17	35,485	419	1,440
Long Beach	L	3,863,000	1,471,000	2,211,000	7,545,000	25	5,658,750	3,143,750	72	43,663	996	3,156
Los Angeles	L	4,716,000	1,900,000	2,727,000	9,343,000	26	6,913,820	3,841,011	83	46,277	1,112	3,454
NYNJ	L	3,396,000	1,415,000	1,899,000	6,710,000	15	5,703,500	3,168,611	70	45,266	1,978	1,602

Source: Adapted from Bureau of Transportation Statistics, 2017; U.S. Army Corps of Engineers, Waterborne Commerce Statistics Center, 2018.

Table 4. Annual inbound, outbound, and empty truck movements and daily inbound, outbound, and empty truck traffic at gates.

Port	Size	Annual Trucks Moving Inbound Containers	Annual Trucks Moving Outbound Containers	Annual trucks Moving Empty Containers	Trucks Moving Inbound Containers per Ship Annually	Trucks Moving Outbound Containers per Ship Annually	Trucks Moving Empty Containers per Ship Annually	Truck Movements per Day (365 Days)	Daily Inbound Gate Traffic (10 Hrs/Day)	Daily Outbound Gate Traffic (10 Hrs/Day)	Daily Empty Gate Traffic (10 Hrs/Day)	Total Gate Traffic per Hour (10 Hrs/Day)
Anchorage	S	136,111	22,778	97,222	1,284	215	917	702	37	6	27	70
Philadelphia	S	148,889	153,889	0	369	381	0	830	41	42	0	83
Baltimore	M	263,333	133,889	137,778	642	327	336	1,466	72	37	38	147
Jacksonville	M	160,067	237,378	205,800	382	567	491	1,653	44	65	56	165
Long Beach	L	1,609,583	612,917	921,250	1,616	615	925	8,613	441	168	252	861
Los Angeles	L	1,938,800	781,111	1,121,100	1,744	702	1,008	10,523	531	214	307	1,052
NYNJ	L	1,603,667	668,194	896,750	811	338	453	8,681	439	183	246	868

Source: Adapted from Bureau of Transportation Statistics, 2017; U.S. Army Corps of Engineers, Waterborne Commerce Statistics Center, 2018.

Table 3. provides order of magnitude estimates of cargo demand and truck movements. On average, gate traffic ranges from 7 (Anchorage) to 105 trucks per hour (Los Angeles). Added to this high demand is the fluctuation in demand based on peaks in vessel arrivals and departures. Ocean carriers are deploying progressively bigger vessels, some that can carry twice the cargo of their predecessors. In this scenario, any number and combination of constraining factors can lead to long truck backups; in recent experience, these have included limited gate capacity and inefficient cargo loading or unloading. Even an insufficient number of available chassis, as in the case of the port of Newark, New Jersey, can lead to miles-long truck lines [21]. Further, high fluctuation in container terminal demand effectively results in capacity at terminal gates that is either too high or too low.

Drayage trucks operate independently of the marine terminal operators and the interaction between the terminal staff and truck drivers and operators is known to be one of the most unpredictable elements of marine terminal operations [22].

While the terminal truck turn time is used to measure performance in marine terminal operations, the more important metric for the drayage trucking industry is the overall turn time for a driver making a delivery. The overall turn time includes the entire duration of time for a driver to start a trip to a terminal, wait in queue at the terminal gate, conduct the transaction within the terminal, and deliver the cargo to the customer. Overall turn time can be influenced by several variables, including:

- Travel distance and roadway congestion between the container terminal and the shipper/receiver (or between container terminal and staging yard/local destination/origin for short-haul drayage).
- Congestion at the terminal gate.
- Delays within the terminal.
- Loading/unloading time at the customer's location [22].

Several approaches to address inefficiencies leading to high turn times have been studied and implemented. ITS technology solutions were studied in an internal state-of-the-practice review in phase 1 of the ITS MARAD program. Many solutions identified in that study are aimed at reducing the barrier between container terminals and the drayage trucking industry through improved transparency and visibility of cargo data. As an example, effort in research and, to a limited extent, in practice has focused on reducing turn times through TAS. The approach involves a vehicle booking system to control the number of trucks arriving at the terminal at different times of day. The main objectives of a well-designed TAS system are to minimize gate queues and ensure effective use of yard container equipment. TAS is used in multiple port facilities in different parts of the world. However, there are several barriers—primarily acceptance by truck drivers—to widespread adoption of TAS in U.S. ports. A concern of truck drivers regarding TAS is the availability of appointments at desired times. Another concern is penalties for missing appointments due to unavoidable circumstances such as traffic [23] (Jovanovik 2019). In some cases, trust issues might already exist between terminal management and truck drivers; truckers may be suspicious of any significant reduction in turn times even if they were to switch to an appointment system versus arriving and queuing up as soon as they got to the terminal. Further, TAS and comparable approaches are likely only effective in addressing delays from recurring or predictable causes. Delays related to specific incidents or one-off operational glitches could still lead to truck backups and congestion inside and outside of the terminal.

Non-recurring Truck Congestion

Risks of several incidents on the container terminal facility increase the possibility of truck delays. The top risks on container terminals based on an analysis of terminal insurance claims are noted below [24]:

- Quay crane incidents involving boom collisions, gantry collisions, or stack collisions.
- Rain and flood damage, particularly from storm surges and floods given that marine terminals are low-lying.
- Straddle carrier collisions and overturns causing property damage or bodily injuries.
- Risks from lift trucks, including forklifts, empty handlers, top-picks, side-picks, reach stacks, etc.; communication errors between the gantry crane operator and driver and lift equipment malfunctions could create issues, as could high-wind conditions that slow or interfere with lift equipment operations; pedestrians are especially vulnerable.
- Risks from trucks and other vehicles on the container terminal facility.
- Collision of ships with the berth or with cranes.
- Stack collisions with yard cranes that can lead to stack collapses causing crane, container, and cargo damage, or even injuries if a container falls on a waiting truck.
- Fire, theft, and poor handling of cargo.

Typical operational situations and inefficiencies that could also lead to higher truck turn times or truck congestion include:

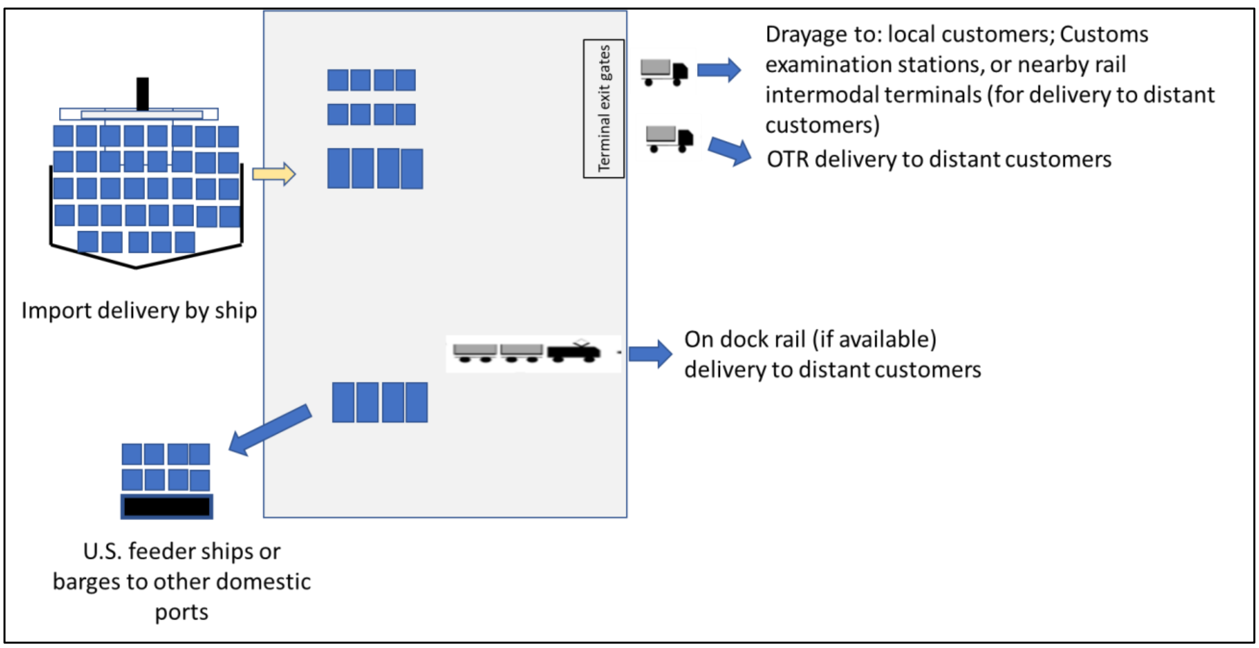
- Drivers pulling the wrong container in wheeled terminals.
- Lift equipment transferring the wrong container in stacked terminals.
- Retrieving containers that require excessive rehandling due to their position in a stack.
- Shift changes for terminal staff.
- General congestion with too many trucks in the terminal.
- Lane blockages from trucks queuing behind a specific crane.
- Computer system breakdowns.
- Poor chassis condition, maintenance, and repair.

Any of the above risks can lead to a disruption in smooth or planned container terminal operations and have a cascading effect on overall container terminal efficiency, including affecting turn times for trucks. Further, the unpredictability of these incidents can make them hard to manage and mitigate.

Short-Haul Drayage Process

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. Drayage used in the shipping industry and logistics is 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]. The project team has refined this general definition to: "Port drayage is the pick up or delivery of containers by truck to a container terminal in which both the trip origin and destination are in the same geographic region." As such all short-distance truck transport of containers to or from the port—no matter if it is an import, export, or transshipment container—is considered port drayage. The following terms and transactions 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 6. Foreign ships may move empty containers from one U.S. port to another U.S. port. Loaded containers, however, can only be transported from one port in the United States to another in the United States 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 in the United States [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 or rail 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 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.



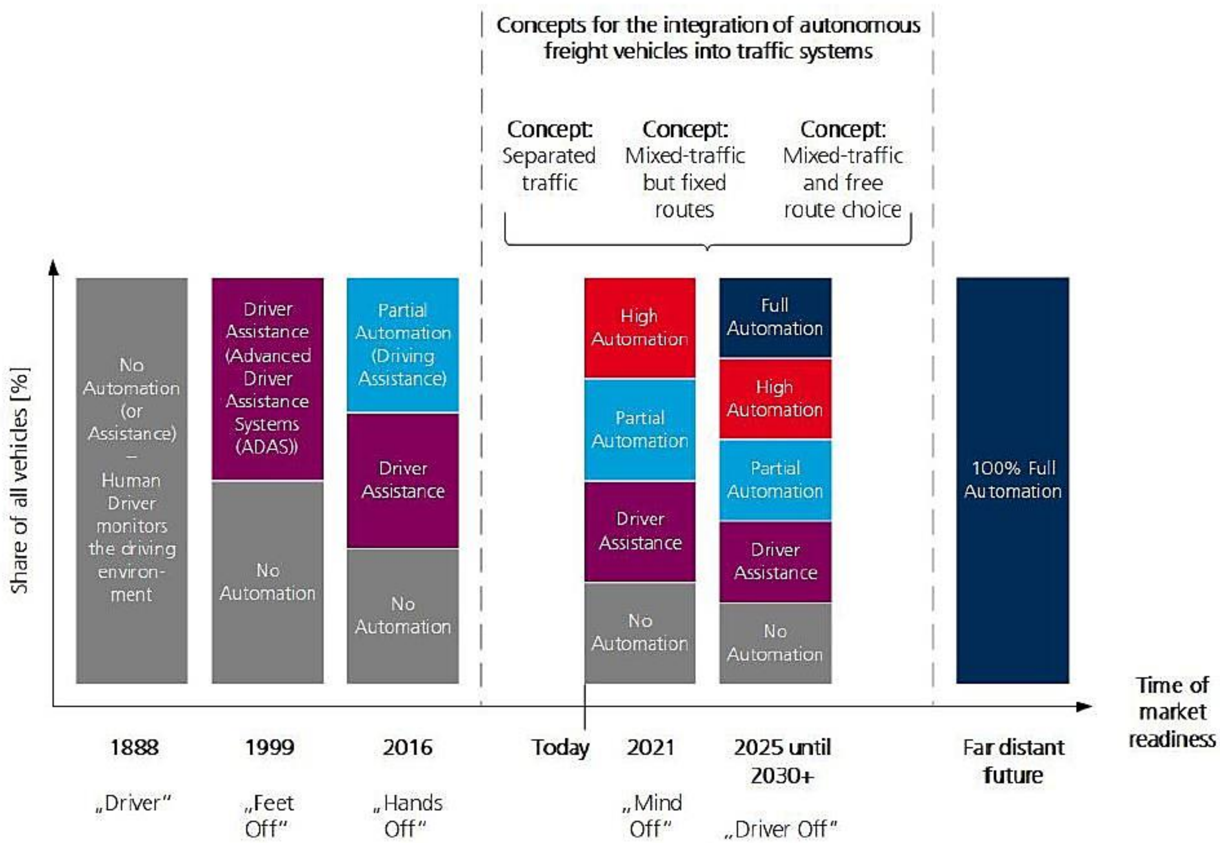
Source: FHWA, 2022.

Figure 6. Diagram. Drayage as part of the import transport chain.

Nature of Changes

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

Figure 7 illustrates the transition to fully autonomous driving on container terminals.



Source: Feidler et al., 2019.

Figure 7. Bar Chart. Future prospects of autonomous driving in container terminals.

Source: Feidler et al., 2019.

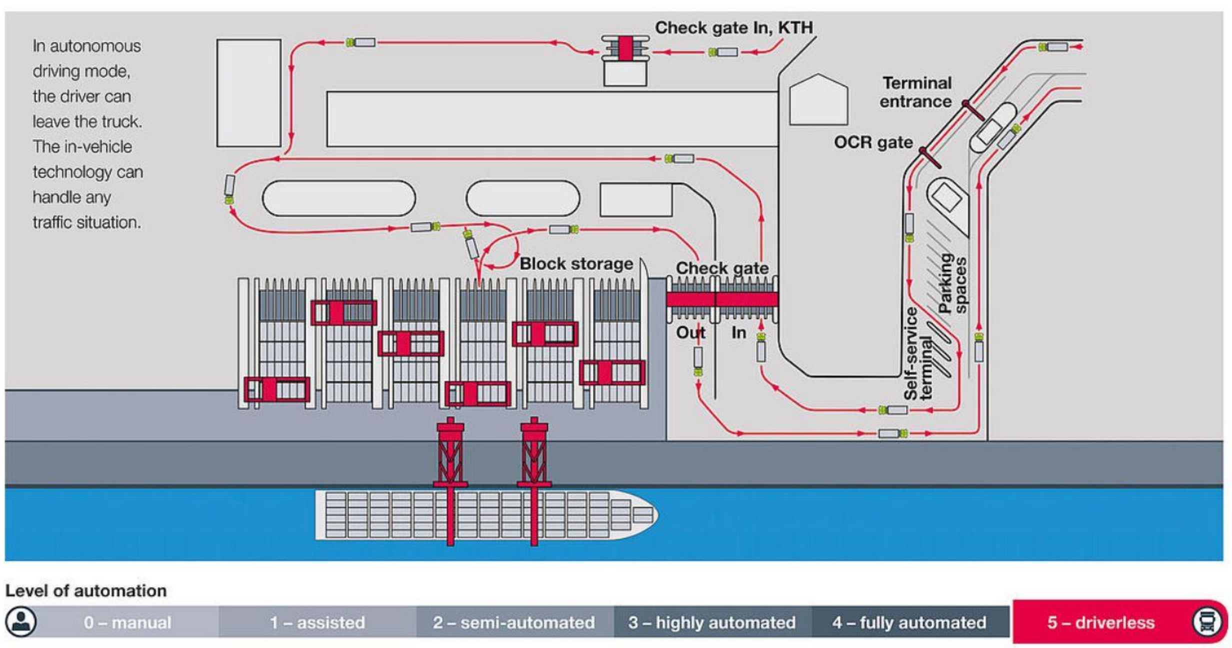
Figure 7 envisions three concepts of implementation of automated road transport within port facilities:

- **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 be enhanced 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 container terminal 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:** This concept requires SAE Level 5 automation, since the autonomous vehicle will be required to perform all the tasks identified in this report under all conditions and situations. It would also place additional requirements on the communications and physical infrastructure.

Source: HLLA, Rise of the Machines, last updated April 1, 2020. [29]

Figure 8 illustrates a pilot SAE Level 3 truck automation project in the Port of Hamburg in Germany. The project is part of a strategic transport partnership between the City of Hamburg and the Volkswagen Group. The project involves Hamburger Hafen und Logistik AG (HHLA) and MAN Truck & Bus. In this project the control handover point occurs at the terminal's entrance and exit gates.



Source: HLLA, Rise of the Machines, last updated April 1, 2020. [29]

Figure 8. Illustration. Port of Hamburg truck pilot: driverless vehicles at a container terminal.

The port handled 126 million tons of cargo in 2020, of which 69 percent was containerized (approximately 8.5 million TEU) [30]. 3 million TEU handled by the port was transshipped to another port and the remaining 5.5 million TEU was transported to or from the hinterlands (inland destination or origin).

Container transport to/from the hinterlands was conducted by truck (50.4 percent), rail (47.0 percent), and barge (2.6 percent). Based on these port data, the project team estimated that 1.7 million truck shipments were needed to transport containers to/from the hinterlands in 2020.

The pilot involves testing an SAE Level 3 truck with a driver present in the vehicle on the road, but with the driver free to do other tasks. At the container terminal gate, the driver can leave the vehicle for it to operate in a fully automated mode for traversing the yard and being loaded and or unloaded by the terminal’s CHE.

Port Operations

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

- **Interaction at the control handover point:** Containers that will be drayed to the container terminal will arrive at a designated control handover point by train or truck. Containers from the container terminal that are destined to be loaded onto a train or transported by OTR trucks will arrive at the control handover point by autonomous drayage trucks. The project anticipates the facility housing the control handover point will be equipped with optical character recognition (OCR) at their entry and departure gates, to automatically identify containers by their unique reference numbers and to identify the trucks and chassis on which they are loaded by their license plates, when containers are delivered or when they depart a control handover point. The facility will have CCTV systems installed so that gate personnel can view the truck cab’s interior and remotely view the outside of the truck/chassis and container to determine if the container is sealed. For the truck to enter the facility, paperwork (actual or electronic) pertaining to the cargo, truck, and driver needs to be in order. To avoid paperwork problems, trucks in this study would not be dispatched until the facility receives confirmation that all paperwork is in order.
- **Interaction at the yard gate:** The first interaction of the automated truck starting from the container terminal facility is entering the yard via a truck 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 with CCTV) by gate personnel 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 [31]. 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 terminal:** 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 [32].
    - 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 infrastructures with U.S. 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 [32]. 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.

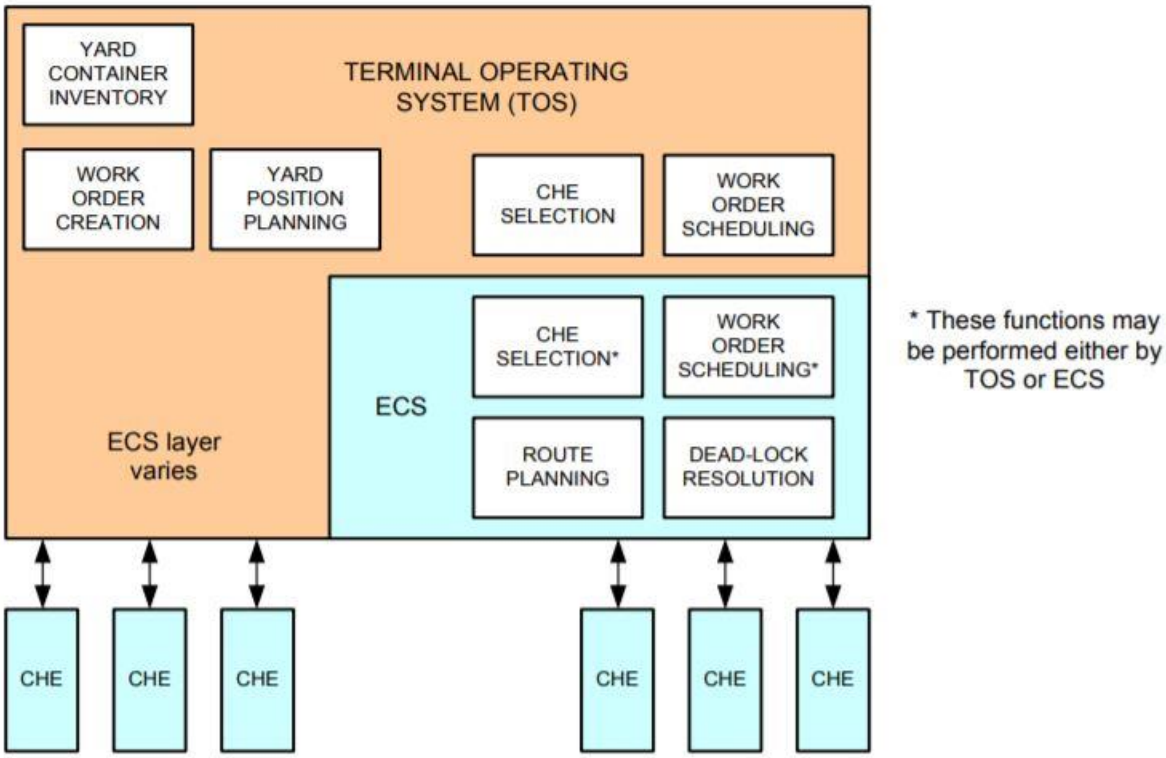
Terminal Management

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 container terminal management that need to be examined or updated to accommodate the proposed concept include:

- **Vehicle and container identification (ID) systems and real-time location:** While OCR is typically used on port facilities for loading/unloading containers and at the yard gate, equipping a container or vehicle with an RFID tag can enable the terminal to track the location of the equipment or container remotely at all times while in the terminal. 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 [32].
- **Terminal operating system:** terminal operating software (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 CHE or group of CHE” [32]. Source: PEMA, Container Terminal Automation, 2016. [31]

Figure 9 illustrates the concept of the relation and interaction between a TOS and an ECS.



Source: PEMA, Container Terminal Automation, 2016. [31]

Figure 9. 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 container terminal operations—the movement of containers throughout ports 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 many ages and conditions. This proposed system assumes compatibility with the existing infrastructure while gaining efficiencies associated with automating drayage tasks within the terminals.

Terminal Capabilities

This ConOps relies on existing centralized systems available in terminals used for maintaining the movement of containers from ships; to the storage yard; and onward to trucks, trains, or other ships outside of the terminal. 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 container 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, contents, and ownership data of relevant containers.
- Weight and load distribution of containers.
- Relevant mapping and container terminal layout data updated immediately following any change.
- Crane location and status of container loading.

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 container terminal in this scenario should also have a robust communications infrastructure. Existing container terminal operations often include manual transmission of information with low throughput that increases 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 ConOps 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 port environment must move around the container 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. 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. First, the operator of a manually operated truck must be able to monitor mechanical problems (through sounds, feel, etc.), and an automated truck must be able to monitor faults and automatically 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., a person walking across the yard, or a stack of containers) and maintaining an up-to-date 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 (e.g., a CMV with a loaded chassis compared to a CMV with no trailer) 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 container terminal operators must now speak the same language to convey information, automated trucks and container terminal control systems must use the same interfaces and data formats to operate efficiently. An automated truck moving through a container terminal requires the ability to take direction from the central container terminal control system and 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 terminal. The truck must also be able to exchange status information with the container terminal and other agents 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 also share the environment with other non-connected and non-automated vehicles and users. Many times drivers can 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

This proposed concept is broken down into transitions and actions throughout the terminal and between the terminal and a control handover point, such as a 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 export and import processes.

Export (Outbound Container)

Container Arriving at the Control Handover Point by Rail or over-the-Road Trucking

When the central truck drayage management system (DMS) receives notice from the railroad or an OTR truck that a container is being delivered to the control handover point, the DMS will record when the container arrived, the location where the container will be stored on the facility, the necessary information (i.e., documents) for the container to be transported to the container terminal (and also identify any missing documentation), and will indicate if the container is available for transport to the container terminal.

Control Handover Point to Container Terminal Gate

If the DMS indicates that a container is available for transport, the DMS will communicate with the container terminal's TAS and the control handover point's YMS to schedule: 1) a time for the truck to enter the control handover point's facility and receive the container and 2) a gate appointment time at the container terminal to enter the container terminal.

The DMS can broadcast either a series of waypoints for the truck to follow, or the location of the control handover point's entry gate and require the truck to determine its own route. The truck then proceeds to the gate and undergoes inspections. Prior to arriving or at the control handover point's entry gate, the DMS will receive information from the control handover point's YMS that states the location in the facility where the container is to be loaded onto the truck. The DMS then broadcasts that information with routing and exit information to the truck, which then moves through the facility to the location. At this point, the truck holds until CHE loads the container onto the truck. Both the truck and CHE transmit data regarding the loading status of the container to the control handover point's YMS that, in turn, forwards the information to the DMS, and when they concur the container is on the truck, the truck departs. The DMS then updates its database with acquired information about the container's status.

The DMS will then broadcast directions for the automated truck to depart the control handover point's facility and proceed to the container terminal gate for inspections and intake.

Terminal Gate to Container Storage Yard

The truck arrives at the gate to the container terminal and undergoes inspections for entry. At the gate or prior to arriving, the DMS transmits to the container terminal's TAS or YMS the documentation necessary for shipping the container. Prior to arriving or at the entry gate, the DMS will receive information from the terminal's YMS that states the location in the terminal where the container is to be unloaded from the truck. The DMS then broadcasts that information with routing and exit information to the truck that moves through the terminal to the location. At this point, the truck holds until the CHE unloads the container from the truck. Both the truck and CHE transmit data about the status of the container to the terminal's YMS that, in turn, forwards the information to the DMS. When the YMS and DMS concur the container is off the truck, the truck departs. The DMS then updates its database with acquired information about the container's status.

Container Storage Yard to Control Handover Point

The truck with an empty chassis will follow routing information it had received upon entry to the port to the container terminal exit, and then proceed back to the control handover point to pick up another container. Alternatively, the truck may proceed to be reloaded within the yard with a container to be carried back to the control handover point, or wait for instructions to move to another location in the terminal and receive a container for transport.

Import (Inbound Containers)

Control Handover Point to Container Terminal

DMS will communicate with the container terminal's TAS and the control handover point's YMS to schedule a time for: 1) the truck to enter the container terminal and receive the container and 2) a gate appointment time at the rail intermodal terminal to enter the control handover point.

The DMS can broadcast either a series of waypoints for the truck to follow, or the location of the container terminal's entry gate and require the truck to determine its own route.

Terminal Gate to Container Storage Yard

The truck then proceeds to the gate and undergoes inspections. Prior to arriving or at the gate, the DMS transmits to the container terminal's TAS or YMS the documentation necessary for shipping the container. Prior to arriving or at the entry gate, the DMS will receive information from the terminal's YMS that states the location in the terminal where the container is to be loaded onto the truck. The DMS then broadcasts that information with routing and exit information to the truck, and the truck moves through the terminal to the location. At this point, the truck holds until the CHE loads the container onto the truck. Both the truck and CHE transmit data about the loading status of the container to the terminal YMS that, in turn, forwards the information to the DMS. When the YMS and DMS concur the container is on the truck, the truck departs. The DMS then updates its database with acquired information about the container's status.

The DMS will then broadcast directions for the automated truck to proceed to the RPM location.

Container Storage Yard to Radiation Portal Monitor

The DMS transmits routing information for the truck to move to the RPM for non-intrusive scanning of the container. If the RPM alerts, the terminal's YMS will notify the DMS to direct the truck to proceed to a designated location in the terminal for secondary scanning by Government personnel. If there is no alert, the DMS will direct the truck to exit the terminal. If there had been an alert and the secondary screening cleared the truck, the terminal's YMS will be updated and the DMS will direct the truck to exit the terminal. At the exit gate the terminal's YMS will record the departure and update the DMS.

Terminal Gate to the Control Handover Point

The truck with a container on a chassis will follow the routing information it had received upon exiting the container terminal to the control handover point. The truck will proceed to the gate of the control handover point's facility and undergo any necessary inspections. Prior to arriving or at the gate, the DMS transmits to the YMS the documentation necessary for shipping the container. Either before the truck enters the control handover point or in response to information provided at the entry gate, the DMS determines the location in the facility where the container is to be unloaded from the truck. The DMS then broadcasts that information to the truck, and the truck moves on its own through the facility to the location. At this point, the truck holds until the CHE unloads the container from the truck. Both the truck and CHE transmit data regarding the loading status of the container to the facility's YMS that, in turn, forwards the information to the DMS. When the YMS and DMS concur the container is off the truck, the truck departs. The DMS then updates its database with acquired information about the container's status.

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 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 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 container 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 container terminal and dedicated control handover point.
CFAD-N14	Need for the automated trucks to be capable of transit between the container terminal and the 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, C-V2X, 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 container 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 container 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 container 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 container terminal and control handover point.	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 point.	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 container 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 container 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 container terminal and control handover point.	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.

References and Notes

[1] For more information on levels of automation, visit https://www.sae.org/blog/sae-j3016-update.

[2] In the preliminary concept used at the beginning of this project, it was anticipated that automated vehicles would be used to shuttle containers between a container terminal and a staging area located several miles from the terminal. Human-driven trucks would then transport these containers to/from the staging area to destination or point of origin. After further investigation, the project team realized the creation of a designated staging area for this purpose was unnecessary and possibly counterproductive. The purpose of the staging area was to serve as a control handover point, where control of the transport vehicle would shift to/from automation to manual. The project team recognized that existing rail intermodal terminals, truck depots operated by over-the-road trucking firms, truck stops, or queuing lines at the terminal could serve as control handover points. As a result, the term “control handover point” replaced the term “staging area” in this document from this point forward.

[3] Some large container terminals have “on-dock rail” and containers are loaded/unloaded from the trains by terminal CHE and no truck drayage is needed.

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

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

[6] National Cooperative Freight Research Program Project 14 – Truck Drayage Practices, https://onlinepubs.trb.org/onlinepubs/archive/NotesDocs/NCFRP14_Task3LiteratureReview.pdf.

[7] Andrew Papson and Michael Ippoliti, Key Performance Parameters for Drayage Trucks Operating at the Ports of Los Angeles and Long Beach (2013), https://calstart.org/wp-content/uploads/2018/10/I-710-Project_Key-Performance-Parameters-for-Drayage-Trucks.pdf.

[8] United States Department of Energy. “Vehicle Weight Classes & Categories.” Alternative Fuels Data Center. United States Department of Energy. June 2021. https://afdc.energy.gov/data/10380.

[9] Hugh R. Morley, “Chassis Explainer: Shipping Industry Seeks Solutions,” Journal of Commerce (July 16, 2018), https://www.joc.com/trucking-logistics/joc-chassis-explainer-shipping-industry-seeks-solutions_20180716.html\.

[10] CBP may have the container drayed to a location outside the terminal for examination or they may inspect the container while it is within the terminal.

[11] United States Government Accountability Office, Radiation Portal Monitors (October 2016), https://www.gao.gov/assets/gao-17-57.pdf.

[12] L. Heilig and S. Voß, “Inter-terminal Transportation: An Annotated Bibliography and Research Agenda,” *Flexible Services and Manufacturing Journal J* 29 (2017): 35–63, https://doi-org.proxy.libraries.rutgers.edu/10.1007/s10696-016-9237-7.

[13] United Nations Conference on Trade and Development. 2019. *2019 e-Handbook of Statistics*. https://unctad.org/system/files/official-document/tdstat44_en.pdf. Accessed March 8, 2020.

[14] American Association of Port Authorities. 2020. Port Industry Statistics. Retrieved from www.aapa-ports.org/unifying/content.?ItemNumber=21048.

[15] U.S. Census Bureau, Population Division. April 2019. “Annual Estimates of the Resident Population: April 1, 2010 to July 1, 2018.”

[16] Knowler, G. 2018. “Forwarders: Unreasonable Demurrage-Detention on the Rise.” *Journal of Commerce* (October 3). Retrieved from https://www.joc.com/international-logistics/forwarders-warn-rising-unreasonable-demurrage-detention_20181003.html.

[17] Energy Information Administration. January 24, 2019. *Annual Energy Outlook 2019 with Projections to 2050*. https://www.eia.gov/outlooks/aeo/pdf/aeo2019.pdf.

[18] H. Im, J. Yu, and C. Lee, “Truck Appointment System for Cooperation between the Transport Companies, and the Terminal Operator at Container Terminals,” *Applied Sciences* 11 (2021): 168, https://dx.doi.org/10.3390/ app1101016.

[19] The Tioga Group, University of Texas at Austin, and University of South Carolina. 2011. *Truck Drayage Productivity Guide*. National Cooperative Freight Research Program Report 11, ISSN 1947-5659. Transportation Research Board, Washington, DC.

[20] The project team found that depending on the particular routes, 80–90 percent of the containers are 40 feet long or more. Some ports count containers longer than 40 feet at 2 TEU, while others might report them as 2.20 or 2.25, as appropriate (there are other lengths as well) reporting is uneven. The conversion factor used for estimating the number of actual containers when volume is reported in TEU ranges between 1.5 and 1.8–1. Because of the under-reporting of TEU, 1.8 is assumed as the most representative of TEU moves per truck.

[21] Campo-Flores, A., and C. McWhirter. 2015. “U.S. Ports See Costly Delays as Cargo Ships, Volumes Grow.” *The Wall Street Journal*. https://www.wsj.com/articles/u-s-ports-see-costly-delays-as-cargo-ships-volumes-grow-1430340113. Accessed March 8, 2020.

[22] Federal Highway Administration. May 2019. *ITS MARAD Truck Staging Study Final Report*.

[23] Jovanovik, R. 2018. “Optimizing Truck Visits to Container Terminals with Consideration of Multiple Drays of Individual Drivers.” *Journal of Optimization* (September 17, 2018). https://www.hindawi.com/journals/jopti/2018/5165124/#copyright.

[24] Safety4Sea. August 22, 2019. “Top 10 Risks Related to Container Terminals.” https://safety4sea.com/top-10-risks-related-to-container-terminals/. Accessed March 8, 2020.

[25] https://www.definitions.net/definition/drayage.

[26] Congressional Research Service, *Shipping Under the Jones Act: Legislative and Regulatory Background* (November 21, 2019), https://crsreports.congress.gov R45725.

[27] Feidler, R., and C. Boss, and D. Gehlken, and K. Brümmerstedt. 2019. Autonomous Vehicles Impact on Port Infrastructure Requirements. Hamburg Port Authority and International Association of Ports and Harbors.

[28] American Public Transportation Association. 2020 "Autonomous and Electric Vehicles." https://www.apta.com/research-technical-resources/mobility-innovation-hub/autonomous-vehicles/. Accessed March 8, 2020.

[29] https://hhla.de/en/magazine/rise-of-the-machines.

[30] https://www.hafen-hamburg.de/en/statistics/.

[31] Minh, C.C., and N. Huynh. 2017. "Optimal Design of Container Terminal Gate Layout." *International Journal of Shipping and Transport Logistics* 9, no. 5 (2017): 640–650.

[32] Port Equipment Manufacturers Association. 2016. *Container Terminal Automation: A PEMA Information Paper*. June, 2016. https://www.pema.org/wp-content/uploads/downloads/2016/06/PEMA-IP12-Container-Terminal-Automation.pdf.

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