Understanding and Modeling Middle-Mile Logistics Automation

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16. Abstract

Middle-mile logistics, particularly drayage which deals with short-distance movements between major transportation facilities in proximity, presents a critical component in the national supply chain. Despite its short distances, drayage incurs a disproportionately large share in the overall shipping cost. The emergence of vehicle automation offers exciting opportunities to improve the efficiency, resiliency, and sustainability of drayage operations, but has received limited attention. To fill this gap, this research adopts a mix of qualitative investigation and quantitative modeling approaches to study the prospects of truck automation in drayage operations. On the qualitative side, we combine harvesting the information from literature and interviewing stakeholders in the field, to understand the challenges and future development process of vehicle automation for drayage operations. On the quantitative side, an mathematical model is developed to seek optimal container and truck flows that minimizes system total cost under varying fleet composition scenarios. We find that vehicle automation would bring significant benefits to drayage operations including timelier movements of containers. The optimal fleet size could be much larger with autonomous trucks. On the other hand, an autonomous driving technology to be adopted by middle-mile freight must demonstrate significant capabilities in terms of safety standard, cost competitiveness, meeting real-world needs, public acceptance, and operation under a proper regulatory environment. A thorough process of testing, incremental deployment, campaigns for public acceptance of ADS on the roads, and the avoidance of overpromising will be needed to gain acceptance and support of the stakeholder groups as well as the public while deploying vehicle automation in drayage operations.

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Middle-mile logistics, drayage operation, automation, trucks, survey, optimization, system total cost, potential issues and challenges

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Executive Summary

Middle-mile logistics, encompassing critical activities such as drayage, plays an essential role in maintaining the fluidity and efficiency of the national supply chain. Despite drayage operations covering relatively minimal distances within intermodal shipments, they disproportionately contribute to overall shipping costs, underscoring the need for improved operational strategies. Recent advances in vehicle automation offer promising avenues to enhance the efficiency and sustainability of these logistics processes. However, the potential, issues, challenges, and impact of automation on drayage operations have garnered limited focus to date.

This research aims to fill this gap. We take a mixed-method approach combining qualitative investigation and quantitative modeling, to study the prospects of truck automation in drayage operations. On the qualitative aspect, we combined harvesting the information from literature and interviewing stakeholders in the field, to understand the potential, concerns, challenges, and future development process of vehicle automation for drayage operations. On the quantitative side, an integer linear programming model in a time-expanded network is developed to seek the optimal container and truck flows that minimizes system total cost, under varying fleet composition scenarios.

Results from the quantitative modeling provides interesting insights about the potential benefits of automating drayage operations. It is found that, as the penetration of autonomous trucks in an existing drayage fleet increases, system total cost decreases thanks to the longer working hours of autonomous trucks without taking a break as required by human drivers. This contributes to timelier movement of containers, which helps reduce the penalty from violating the time window for container pickup and delivery. In addition, if a drayage operator could freely determine its optimal fleet size, the optimal fleet size of autonomous trucks would be much larger than the optimal fleet size of conventional trucks. Despite incurring more truck operating cost and depreciation cost, a larger fleet of autonomous trucks allows for timelier pickup and delivery of containers, which reduces time penalty cost and leads to a reduction of the system total cost.

While the quantitative modeling provides an overall positive prospect of drayage automation, a different angle is offered by the qualitative investigation, focusing on the potential issues and challenges that need to be addressed. The stakeholders that we interviewed suggest that an autonomous driving technology to be adopted by middle-mile freight must demonstrate significant capabilities in terms of safety standard, cost competitiveness, meeting real-world needs, public acceptance, and operation under a proper regulatory environment. A thorough process of testing, incremental deployment, campaigns for public acceptance of autonomous driving systems (ADS) on the roads, and the avoidance of overpromising will be needed to gain acceptance and support of the stakeholder groups as well as the public while deploying vehicle automation in drayage operations. Finally, while achieving full automation may take some time, stakeholders should remain open to various other technological innovations including partial vehicle automation, and require full automation to prove itself useful before harnessing its power in drayage operations.

Introduction

Middle-mile logistics, particularly drayage which is a specific type of middle-mile operation dealing with short-distance movements between major transportation facilities in proximity, presents a critical component in the national supply chain. Despite representing a small fraction of the total distance covered in intermodal shipments, drayage incurs a disproportionately large share of the overall shipping cost. An earlier estimate suggested that drayage accounts for 25-40% of origin-to-destination expenses (Macharis and Bontekoning, 2004). In addition, when drayage movements occur in metropolitan regions, they exacerbate existing traffic congestion on already crowded road networks. The emergence of vehicle automation offers exciting opportunities to improve the efficiency, resiliency, and sustainability of drayage operations. Yet, it has not received adequate research attention.

To fill this gap, this project adopts a mix of qualitative investigation and quantitative modeling to study the prospects of truck automation in drayage operations. On the qualitative side, we combine harvesting the information from literature and interviewing stakeholders in the field, to understand the challenges and future development process of vehicle automation for drayage operations. Interviews were carried out with stakeholders from prominent freight hubs, such as the Chicago and the Los Angeles metropolitan regions to obtain practical perspectives on how automation can enhance middle-mile logistics and challenges that have to be addressed before such technology can be adopted. Through this, we gain valuable insights into possible deployment scenarios, and the challenges and opportunities presented by the automation of drayage operations. We also strive to obtain data from the interviewees that can facilitate mathematical modeling of middle-mile operations.

On the quantitative side, an integer linear programming model in a time-expanded network is developed to seek optimal container and truck flows that minimizes the system total cost. The system total cost consists of truck operating cost, truck depreciation cost, and container time cost, the latter due to the finite time window for pickup and delivery of each container. In the modeling setting, we consider several cases with different fleet compositions, including only conventional trucks, a mix of conventional and autonomous trucks, and only autonomous trucks in the drayage fleet. Conceptually, an autonomous truck is more expensive than a conventional truck, but having autonomous trucks brings benefits of lower unit operating cost and longer working hours without taking a break as required by human drivers. In the analysis, we investigate the tradeoff under a range of autonomous truck penetration scenarios, and strive to identify the optimal fleet size when operating a conventional fleet and an autonomous fleet.

By doing the above, this project aims to provide qualitative and quantitative insights and consequently policy recommendations that can help set possible pathways for drayage automation and related operations management. Ultimately, the outcome of this study will help pave the way for a more efficient and sustainable drayage sector that can significantly contribute to the improvement of the national supply chain. In this vein, this study also supports the US DOT strategic goal of Economic Strength and Global Competitiveness by enhancing freight movement in middle-mile in the US. In addition, the project will help the US DOT with the strategic goal of Transformation, and Climate and Sustainability, by promoting automated vehicle deployment in drayage operations.

In the rest of the report, we first conduct review of the existing literature, on the US trucking industry and the middle-mile problem in the Chicago metropolitan region, existing models for drayage operations, and autonomous driving systems. Then, we describe the research approaches for the qualitative part (surveys) and the quantitative part (optimization modeling) respectively. This is ensued by presentation of the research results, again first from the surveys and then from the optimization modeling. We also discuss a potential model extension focusing on developing a customized solution algorithm to potentially solve the optimization model in a more efficient manner. In the end, we summarize the study findings and conclude.

Literature review

The research begins with a literature review with three purposes. First, to gain a fundamental understanding of autonomous driving systems (ADS), the modern supply chain, the middle mile, and drayage within and without ADS. Second, to understand contemporary concerns of vehicle automation and professionals who work in the supply chain industry. Third, to prepare questions for the interview portion. Because of the need to understand contemporary thought in the field, the literature review was split between research and academic articles, and industry publications and reporting. The non-academic sources are included because they reflect the concerns, beliefs, and other tendencies of thinking by professionals in the ADS and trucking industries. These concerns are important to understand for the development of questions.

The US trucking industry and the middle-mile problem in the Chicago region

The US trucking industry plays a critical role in the national economy and is faced with many contemporary issues. The American Transport Research Institute's (ATRI) annual Top Ten Issues in Trucking reports were consulted to determine if ADS could solve contemporary issues in trucking (ATRI, 2021; 2022; 2023). Not all the identified issues by fleet operators and management, such as fuel prices and overlitigation, could be addressed by truck autonomation. The fear of crashes causing expensive payouts is reported across the trucking industry. These cases are known as "nuclear verdicts". The belief that juries are biased against trucks and their drivers is widespread in trucking. In addition, operators will be hesitant to introduce vehicle automation to their fleets if doing so opens them to more such liability (McLennan, 2024).

However, a major identified issue by both research and industry publications is the shortage of truck drivers. With labor accounting for one third of the cost in trucking (Kitroeff, 2019), efforts to ameliorate the shortage include the lowering of minimum driver ages, efforts to recruit female drivers, and even, in a crisis, the deployment of the army in the UK (Lawrence, 2021; ATA, 2021; Taylor, 2021). Therefore, a major question for all interviewees concerned the capabilities of modern ADS to replace trained truck drivers.

Specific to the Chicago metropolitan region, which has long served as a national freight hub, unique opportunities and challenges exist for truck automation, either comprehensively or as a pilot program. In 2023, Chicago had the second, sixth, 12th, 22nd, and 24th worst trucking bottlenecks nationwide (ATRI, 2023). Drayage in Chicago is complicated by the presence of as many as 19 operational intermodal rail yards, with drayage moving goods between them. These yards are small and aging, but Chicago's status as a national rail hub means they must handle large amounts of traffic (Schultz, 2023). While the concentration of many intermodal rail yards makes Chicago an attractive location to implement middle-mile automation, any vehicle automation project in Chicago would have to account for this situation.

Modeling drayage operations

For the past twenty years, the literature on modeling drayage operations have looked into various static and dynamic drayage problems with a concentration on drayage truck scheduling. Asymmetric multiple traveling salesman problem with time windows (am-TSPTW) has been a popular model to study drayage truck scheduling. Wang and Regan (2002) used am-TSPTW and proposed a time window reduction and partitioning method to solve the problem more efficiently. Ileri et al. (2006) proposed an approach for planning daily drayage operations with repositioning of empty containers. Current literature has focused on problem with variant number of depot and terminals. Problems with both single and multiple terminals were studied, with extensions to drayage with limited number of empty containers (Zhang et al., 2009; 2010; 2011). In particular, the consideration of limited empty containers is to helps drayage company to find better container rebalancing strategy. Imai et al. (2007) considered the truck pickup and delivery problem as am-TSPTW as well. Their proposed model involves multiple intermodal terminals.

More recently, Lai et al. (2013) proposed a truck scheduling problem with heterogeneous truck fleet with single and double container loads. Zhang et al. (2015) proposed a multi-size container drayage model with single terminal and single depot, they proposed three tree search procedures and an improved reactive tabu search algorithm to solve the problem. Song et al. (2017) studied a separation mode of drayage operation which allows containers to be separated from truck during loading/unloading operation. The problem was formulated as asymmetric vehicle routing problem with time windows (a-VRPTW) and solved by a branch-and-price-and-cut algorithm.

Dynamic truck scheduling models provide a feasible way to study drayage problem with flexible tasks. Jula et al. (2005) solved the am-TSPTW using a two-phase exact algorithm and dynamic programming. Smilowitz et al. (2006) modeled a drayage problem as a multi-resource routing problem with flexible tasks and solved the problem by a column generation method embedded in a branch-and-bound framework. The dynamic method can also solve drayage problem with heterogeneous truck fleet. Cheung et al. (2008) proposed an attribute-decision model for cross-border drayage problem in the Hong Kong area. Zhang et al. (2014) solved a container drayage problem with flexible tasks by a window partitioning-based strategy. As can be seen, the existing literature is dominated by formulating and applying VRPTW or TSPTW to tackle various versions of the drayage operation problem. On the other hand, characterizing the spatial-temporal feature of the problem in a time-expanded network setting has not been considered.

As an efficient way to collaborate terminals and truck companies, Terminal Appointment System (TAS) has also been studied by several researchers. Namboothiri et al. (2008) generated a port access appointment system using unconstrained drayage problem, which is a special case of pickup and delivery problem with time windows (PDPTW). The authors found that TAS can generate benefits to increase the efficiency of drayage operations. Shiri et al. (2016) studied a drayage truck appointment system associated with truck scheduling. The multiple depots and single terminal system model was solved by a reactive tabu search method. In drayage context, the capacity constraints are more reflective to real-world conditions since all terminals have finite capacity.

With the recent development of autonomous truck, the drayage modeling literature has just started exploring the potential impact of vehicle automation on drayage operation. You et al. (2020) investigated a local drayage problem (LCDP) with semi-automated drayage truck platooning, in which only the leading truck in a platoon is human-driven. Chen et al. (2021) proposed an autonomous truck-based scheduling problem for container transshipment between two seaport terminals. Autonomous trucks are allowed to travel in a platoon with short distance. Xue et al. (2021) stated that the semi-autonomous platooning mode benefit the system by saving labor cost, saving fuel cost and air contamination reduction. The limited literature has shown autonomous truck brings energy and labor cost savings in drayage operations. However, the specific effects of different proportions of autonomous trucks within a fleet on the drayage system remain underexplored.

Autonomous Driving Systems

A key enabler of drayage automation is the Autonomous Driving System (ADS). The mechanics of ADS have been studied and tested for many years. Generally, a modern ADS consists of three parts (Figure 1):

- **Input**: collecting information from the environment around the vehicle. This uses a combination of Light Detection and Ranging (LIDAR), Radio Detection and Ranging (RADAR), cameras, and integrated Global Positioning Systems (GPS).
- **Process**: the ADS interprets inputs to create a real-time map of its environment and nearby objects, then determines driving behavior.
- **Output**: the ADS controls steering, acceleration, braking, and other functions of the vehicle.

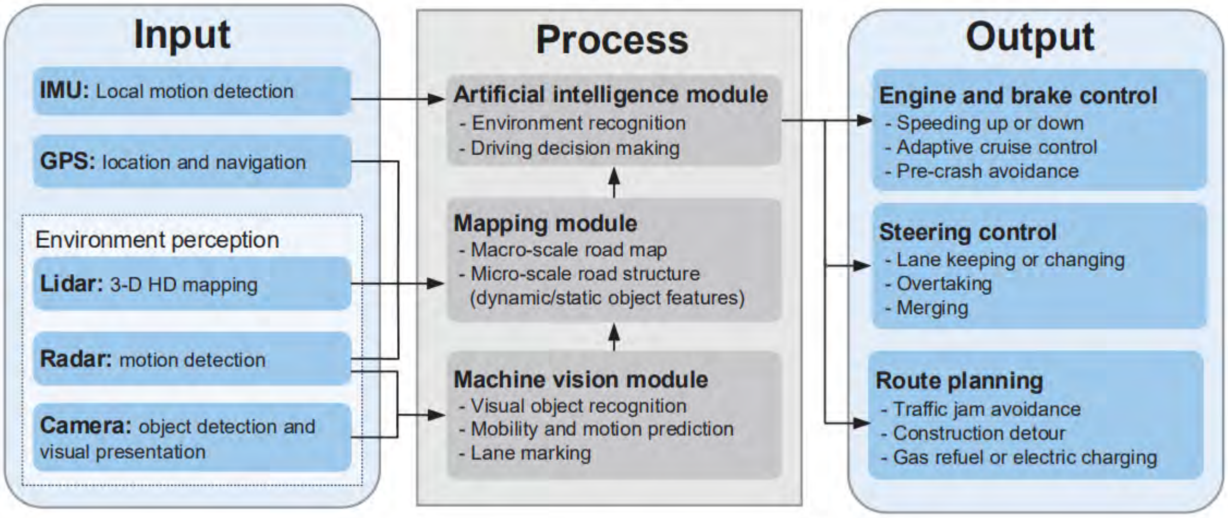


Figure 1: The ADS decision-making process (source: Zhang et al., 2018)

This system tends to be vulnerable to poor driving conditions such as low visibility, inclement weather, and traffic congestion. As such, ADS pilots have happened first in sunny states like Arizona and Texas. It is generally believed that developers are likely to target the long-haul and middle-mile sections of the trucking industry before short-haul driving in dense cities.

Another contemporary area of inquiry in vehicle automation technology development is vehicle-related communications, either between vehicles (V2V), or between a vehicle and nearby infrastructure (V2I). With significant deployment of V2I infrastructure and capabilities, ADS can receive better real-time information about its surroundings and roadway conditions, potentially improving driving, safety, and efficiency (Zhang et al., 2018).

It is worth noting that the regulatory environment surrounding ADS is dynamic. The federal government has released multiple version of autonomous vehicle development guidance. The latest federal-level guidance is the Autonomous Vehicles Comprehensive Plan of 2020 promulgated by the US Department of Transportation (2020). This Plan outlines three priorities for ADS development: safety, stakeholder input, and remaining technology-neutral. The latter refers to a policy of not favoring any specific implementation of ADS through funding or regulation, with the goal of encouraging innovation. With the rapid development in ADS since 2020, there is growing industry pressure for regulatory bodies to end technology neutrality and articulate a more specific policy. ADS developers feel that without clear regulation, they are at risk of developing technology or building vehicles which future regulation may make illegal.

Areas of inquiry

Based on the review of the literature, we identified 14 areas of inquiry that have been considered and are related to ADS. These 14 areas served as the starting points for the development of questions for interviews. Depending on the interviewee's position, only certain questions were asked. For instance, vehicle automation professionals would not be provided with questions about Chicago drayage.

Issues in Contemporary Drayage - the major problems and bottlenecks facing middle-mile operators in the interviewee's region of expertise. For the majority, this was the Chicago area. Also including discussion on how identified problems could best be addressed, and whether ADS would be effective.

Quantitative Information - Drayage data such as the share of cargo being transported by 40' trucks. This information was used by the engineering/modeling team.

ADS Adoption: Role and Timeline - The interviewee's opinion on the timeline of ADS adoption and where in the chain it would be used first.

ADS Adoption: Economics - The costs and savings associated with ADS, how it would affect the bottom lines of companies using the technology. The impact of ADS adoption on the market share of small and large companies.

ADS Adoption: Labor - The positions created and made obsolete by the adoption of ADS. The response of labor organizers to ADS. Potential for retraining the workforce.

Labor Shortages - The phenomenon of labor shortage in the supply chain, especially truck drivers. Current efforts to ameliorate the problem and the potential impact of automation.

ADS and Public Policy - The reactions of policymakers to ADS. Current and potential regulations. Necessary conditions for public acceptance of automated trucks.

Pilot Programs - Existing and potential programs for testing ADS. Limits of these tests. The characteristics of a useful ADS pilot program.

Vehicle-to-Infrastructure Communication - The potential for implementing V2I and its impacts on the transportation system and supply chain.

Information and Data - Contemporary developments in data tracking and use in the supply chain. Need for and possibility of information sharing between firms.

Cybersecurity - Potential issues surrounding security of ADS and V2I systems and data. Possible safety solutions.

Automation in Intermodal Yards - Contemporary use of automation in IM yards. The process and extent of adoption. Benefits and drawbacks.

Environmental Impacts - Potential for middle-mile automation to improve environmental outcomes.

Insurance and Liability - Issues and predictions surrounding insuring automated vehicles. Perspective of insurance companies and fleet operators. Liability for crashes and litigation.

In the next two sections, we provide an overview of the study approaches. For the qualitative part of the study, we describe how interviews were planned and conducted and how the analysis of the collected data was carried out. Then, we switch to the quantitative part of the study, which focuses on introducing a mixed fleet drayage operation problem with soft time windows. The problem is presented in a time-expanded network flow setting.

Research approach (I): Qualitative part

Overview of the interviews

The objectives of the interviews were to obtain insights into various aspects of middle-mile automation and also gather some necessary information that can help our modeling effort. To obtain insights, we formulated questions that cover the key topics identified from the literature review. The information related to modeling included the distribution of container sizes, organization of drayage industry, etc. Utilizing actual data helped the modeling effort be more realistic.

Interviews were conducted between May 2024 through August 2024. Interviews used a semi-structured format in which interviewees were asked a set of questions that were developed before the interview, although some customizations were made to fit the interviewee's backgrounds. The interviews were conducted using an online meeting application that allowed us to record the discussions and also generated transcripts automatically. Computer-generated transcripts were reviewed for accuracy and edited if needed. Each interview lasted between 45 minutes and 1 hour.

Analysis of the transcripts involved a structural text analysis using ArtConc (Anthony, 2024) software and also detailed reading and interpretation of the transcripts in a complementary manner. Text analysis uses statistics and significance tests to "objectively" evaluate a set of texts, or "corpus". Interpretation of the discussions recorded in the transcripts is inherently subjective. Text analysis can be used to validate interpretations against data.

Recruitment of interview subjects

The research team used a combination of reaching out to the experts known in the field and snowball sampling in which interviewees are asked to recommend other professionals who can provide insights on the issues discussed during the interview. In the first stage, a list of possible interview subjects were generated based on: personal contacts of research team members, membership lists of government committees related to freight, and organizations and individuals that appeared frequently in reviewed literature. The names in the list were organized into public sector, operators, labor and trade organization, and automated system developers. The invitation emails were sent to potential interviewees from the list.

A total of 50 individuals were contacted, which resulted in nine interviews. Two individuals agreed to be interviewed, but interview was not conducted due to a difficulty with scheduling. Interviews were carried out between May 2024 and August 2024. The breakdown of the professional fields of the interviewees are: public sector (four), operators (three), labor and trade organizations (two), and automated system developers (none). The response rate was lower than expected compared against research team's past experience. One possible explanation is that there was another large-scale interview effort on smart logistics was being carried out in the time period that mostly overlapped with our effort. In terms of automated system developers, there were not many that focused on trucks and other terminal equipment , and such companies are often reluctant to share information. Public sector participants included professionals who work for municipalities and metropolitan planning organizations (MPOs). One of the operator participants was a consultant with a background in the trucking industry.

Interview questions

Interview questions, included Appendix A, were developed based on the 14 issues identified from the literature review. As mentioned earlier, we tailored some of the questions depending on the background of the interviewee. To encourage interviewees to freely express their insights, the research team encouraged expanding discussions into topics that are related or complementary to the questions being asked. As such, the interview questions were used to give a structure, rather than confining, the discussions.

Questions were grouped into broad topical areas including:

- State and operation of the middle-mile freight;
- Data for use in the modeling effort;
- Prospect for middle-mile automation, e.g. technology, market condition, advantages, disadvantages, regulatory issues, impacts, etc.;
- Path to pilot testing.

In most cases, the term “drayage” was used interchangeably with middle-mile as some of the interviewees were not familiar with the latter term.

We find that not all the interviewees offered insights into specific questions. Some interviewees stated that they do not have sufficient knowledge to discuss particular question in detail. Others simply did not show interest in answering questions related to particular subject, and quickly changed the subject. In some cases, research team made similar judgement based on the background and the knowledge level of the respondent. Table 1 below shows the number of interviewees who discussed each of the 14 topics. It should be noted that these topics have significant overlaps. Conversations were free-flowing and information not related to any of the above topics was discussed. We generally found that nearly all the interviewees were able to provide an in-depth analysis of existing conditions and issues related to drayage. However, as the conversation turned to future adoption of ADS in drayage, many of the interviewees were not able to share useful insights, which is indicative of the unexplored nature of the topic. In the same vein, some interviewees struggled to discuss possible impacts of middle-mile automation in specific terms.

Table 1. Interviewee responses counted by topic

Topic	Interviewee Responses
Issues in Contemporary Drayage	9
Quantitative Information	4

ADS Adoption: Role and Timeline	6
ADS Adoption: Economics	7
ADS Adoption: Labor	8
Labor Shortages	4
ADS and Public Policy	7
Pilot Programs	5
Vehicle-to-Infrastructure Communication	5
Information and Data	4
Cybersecurity	4
Automation in Intermodal Yards	3
Environmental Impacts	2
Insurance and Liability	3

Research approach (II): Quantitative part

Problem representation in a time-expanded network

As mentioned in the previous sections, this study adopts a time-expanded network to represent the terminal-to-terminal drayage operation system with soft time windows and limited capacity for terminals. We choose to focus on terminal-to-terminal operation as such kind of drayage operations present a more suitable environment for the deployment of truck automation. First, a terminal-to-terminal network typically involves limited complicated local roads, which reduces the challenges for autonomous driving. Second, a terminal-to-terminal drayage network is relatively simple since the number of terminals is fewer than the number of distribution center customers, as in the case of terminal-to-distribution center drayage. Third, a terminal-to-terminal network allows for higher speeds for trucks and provides a more favorable scenario for automated operations of the trucks.

We model a drayage system as either a single fleet of homogeneous trucks or a mixed fleet of autonomous and conventional trucks, to meet the daily demand for terminal-to-terminal container movement. The objective is to minimize the total cost of operating the system given the truck fleet. Each container has a time window delimited by the earliest time for pickup and latest time for delivery. When a time window is violated, a penalty cost will incur depending on the amount of violation.

To model the flow of trucks and containers, we adopted a time-expanded network, which seeks to integrate physical transportation networks with temporal representation of vehicles, commodities (or travelers, in the case of personal transportation) and capture their spatial-temporal characteristics. Time-expanded networks have been widely used in transportation network modeling literature (Yang, 2020; Zhao, 2018; Scherr, 2020). The most related literature that applies network flow problem to freight transportation is the service network design problem (SNDP), which is mostly used to designate the strategical issues of scheduling of service for terminal operations (Crainic, 2000). Specific for drayage, a variety of models have been developed to reduce operating cost and improve operational efficiency. However, only a few recent studies attempted to combine the autonomous truck, terminal capacity, and container soft time window together.

Our model is set up as follows. Consider a directed, connected traffic network (N, A), where N denotes the set of space-time nodes representing the terminals of containers. A is the set of arcs representing the connections between any terminals. To extend the network to time-expanded network, the daily working hours are discretized into a set of time points, denoted by $t_0, t_0 + \tau, \dots, t_0 + s\tau$, with a uniform time interval τ between each two time points. The extension of a physical network to a corresponding time-expanded network allows for depicting the container time schedule, without adding extra time window constraints to the formulation. The illustrative example in Figure 2 shows the time-expanded formulation of the container transporting process, where we can see the terminal numbers on the left side and the time points at the bottom, denoted by $t_0, t_0 + \tau, \dots, t_0 + s\tau$. Each node represents the state of corresponding terminal at the current time. In particular, we distinguish the autonomous truck arcs and conventional truck arcs with two different traveling arcs - the blue dash line and black solid line.

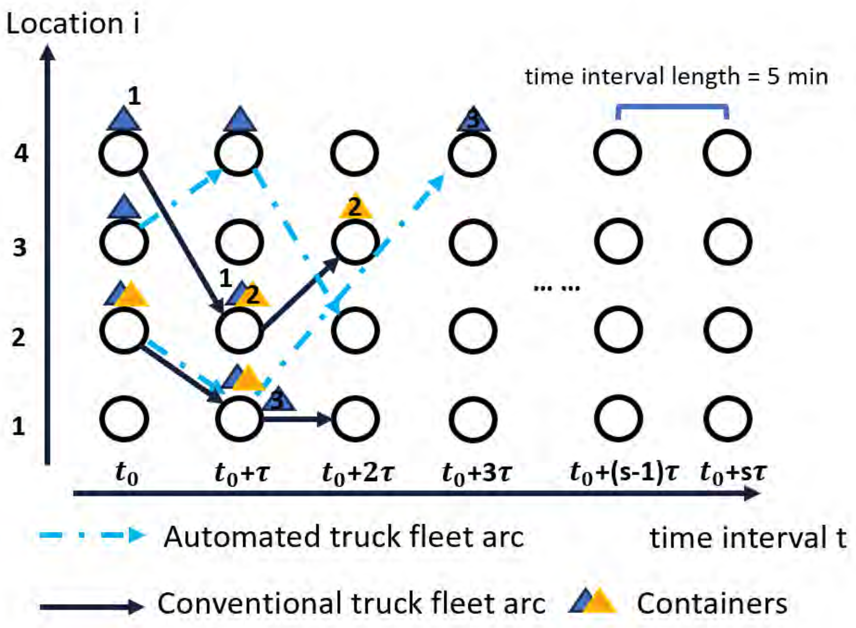


Figure 2: Time-expanded network

For each container, a time-expanded network can also be characterized as shown in Figure 3. The solid lines indicate the traveling or waiting trajectory of each container on the physical network. In order to address the soft time window in our problem, we introduce the auxiliary node and auxiliary arcs which are only available to delivered containers or containers that are failed to be delivered. Denoted by the black dash circle and black/red dash line in the figure, the auxiliary nodes and arcs serve as the exits of container.

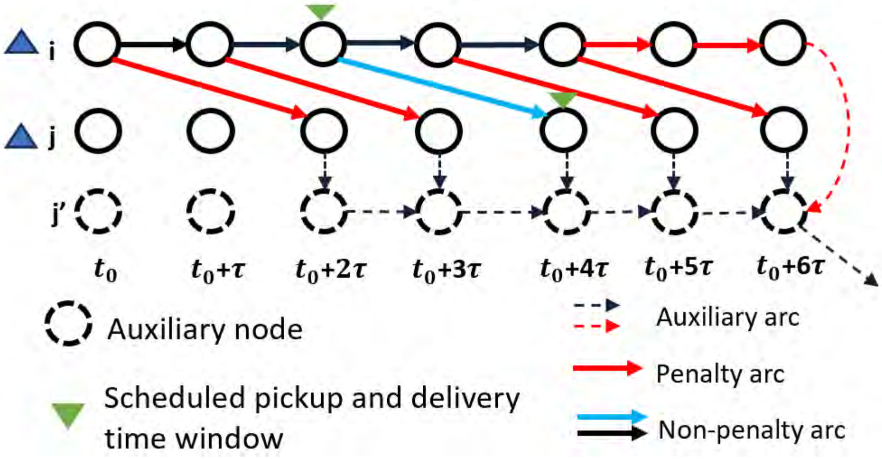


Figure 3: Container time-expanded network

For each container, the existence of auxiliary nodes and auxiliary arcs allow the delivered container flow to be moved out of the main network. In Figure 3, the time interval between two green triangles is the scheduled time window where completion of order does not incur penalty cost. The penalty arcs with extra cost are those red solid lines. The details of both container arcs and truck arcs are listed below:

- *Container arc.* Container 2 is picked up at $t_0 + \tau$ at terminal 2 and delivered at $t_0 + 2\tau$ to terminal 2 traveling one time interval, so the arcs before time point and after time point $t_0 + 2\tau$ are considered as penalty arcs with higher travel cost as penalty. Similarly, container 3 is picked up at $t_0 + \tau$ at terminal 2 and delivered at $t_0 + 3\tau$ to terminal 4. In Figure 2, the container is scheduled to be picked up at time point $t_0 + 2\tau$ at terminal i and delivered at time point $t_0 + 4\tau$ at terminal j. The container is allowed to be picked up earlier than $t_0 + 2\tau$ and delivered later than $t_0 + 4\tau$ due to the existence of soft time window but with an extra penalty cost (If so, the container will have to travel through the red penalty arc).

- *Truck arc.* As noted in Figure 3, the black solid line and blue dashed line indicate the conventional truck arc and autonomous truck arc respectively. In this case, one autonomous truck travels from $(3, t_0)$ to $(4, t_0 + \tau)$ then to $(3, t_0 + 2\tau)$, the other travels from $(2, t_0)$ to $(1, t_0 + \tau)$ then to $(4, t_0 + 3\tau)$. On the other hand, one conventional truck travels from $(1, t_0)$ to $(2, t_0 + \tau)$ then to $(3, t_0 + 2\tau)$, the other one travels from $(2, t_0)$ to $(1, t_0 + \tau)$ and waits at terminal 1 for τ time.

Now let us consider a group of container orders waiting for transfer at multiple terminals to their destination terminals by drayage companies. For each container, its earliest pickup time and latest delivery time are given. Drayage companies operate the service using both conventional trucks and autonomous trucks, leading to varying investment and driver costs among terminals located in an urban area. During their service time, an idle truck can pick up a new container order, either from the same terminal or by going to a different terminal for pickup. We assume that trucks start and end their service at a depot in a day. Additionally, we assume that all containers are homogeneous. Each truck can only transport one container at a time. Due to the different features of autonomous trucks and conventional trucks, there can be significant differences in the investment and operational costs of running different types of truck fleets. Therefore, our mixed fleet drayage problem aims to answer the following question: How does automation affect our drayage service cost in terms of energy and operation?

In the remaining of this section, we first present the mathematical notations (sets, parameters, etc.) and the variables in the optimization model. Based on these notations, the mathematical model is then formally introduced.

Relevant notations

The mathematical notations used in our model are presented in Table 2 below.

Table 2. Mathematical notations

Notation	Description
$\mathcal{N}$	Set of nodes

$\boldsymbol{\mathcal{A}}$	Set of arcs
$\boldsymbol{\mathcal{N}'}$	Set of container dummy nodes
$\boldsymbol{\mathcal{P}_n}$	Set of penalty arcs for container n
$\boldsymbol{\mathcal{A}'}$	Set of container dummy arcs
$\boldsymbol{\mathcal{R}}$	Set of containers
$\boldsymbol{\mathcal{T}}$	Set of time intervals
$\boldsymbol{\mathcal{L}}$	Set of lunch time intervals
$\boldsymbol{\mathcal{C}}$	Set of truck types
$\boldsymbol{n}$	Index of containers, $n \in \mathcal{R}$
$\boldsymbol{m}$	Index of truck types, $m \in \mathcal{C}$
$\boldsymbol{(i,t)}$	Index of space-time nodes, $(i,t) \in \mathcal{N}$
$\boldsymbol{(i,t),(j',t')}$	Index of space-time arcs, $(i,t),(j,t') \in \mathcal{A}$
$\boldsymbol{(j',t)}$	Index of container space-time dummy nodes, $(j',t) \in \mathcal{N}'$
$\boldsymbol{(j,t),(j',t')}$	Index of container space-time dummy arcs, $(i,t),(j,t') \in \mathcal{A}$
$\boldsymbol{c^m_{(i,t),(j,t')}}$	Cost of a truck type m transporting one container on arc $(i,t),(j,t')$
$\boldsymbol{c^n_{(i,t),(j,t')}}$	Auxiliary traveling cost of container n on arc $(i,t),(j,t')$
$\boldsymbol{c^p_i}$	Pickup capacity at terminal i
$\boldsymbol{c^d_i}$	Delivery capacity at terminal i
$\boldsymbol{p^n_{(i,t),(j,t')}}$	Penalty for early pickup or late delivery
$\boldsymbol{K_m}$	The number of trucks of type m
$\boldsymbol{\tau}$	Time interval length

Furthermore, we define two sets of decision variables: (1) integer variable $x^m_{(i,t),(j,t')}$, which denotes the number of trucks of type m that leaves terminal i at time t and arrives at terminal j at time t', and (2) binary variable $z^n_{(i,t),(j,t')}$, which equals one if container n is transported on space-time arc $(i,t),(j,t')$, and zero otherwise. These are shown in Table 3.

Table 3. Variable description

Variable	Definition	Type
$\boldsymbol{x^m_{(i,t),(j,t')}}$	Flow of trucks of type m from node (i,t) to node (j,t')	Integer
$\boldsymbol{z^n_{(i,t),(j,t')}}$	Flow of container n transported from node (i,t) to node (j,t')	Binary

In our problem, waiting arcs and traveling arcs of trucks are denoted by the set of variables $\{x^m_{(i,t),(j,t')}\}_{i=j\cup(i,t),(j,t')\in\mathcal{A},m=\{1,2\}}$ and $\{x^m_{(i,t),(j,t')}\}_{i\neq j\cup(i,t),(j,t')\in\mathcal{A},m=\{1,2\}}$ respectively. Here, $m=1$ corresponds to conventional truck; $m=2$ corresponds to autonomous truck. Container waiting arcs and traveling arcs are similarly denoted. Particularly, we define penalty arc set $\mathcal{P}_n \subseteq \mathcal{A}$ as a special type of waiting arc or traveling arc with higher cost.

Model formulation

With the above definitions of notations and variables, we now present the optimization model for drayage operations with a mixed fleet of autonomous and conventional trucks.

$$\min \quad \sum_{m\in\mathcal{C}} \sum_{(i,t),(j,t')\in\mathcal{A}} c^{m}_{(i,t),(j,t')} x^{m}_{(i,t),(j,t')} \quad + \quad \sum_{n\in\mathcal{R}} \sum_{(i,t),(j,t')\in\mathcal{P}_n} p^{n}_{(i,t),(j,t')} z^{n}_{(i,t),(j,t')}$$

$$- s \sum_{(i,t),(j,t')\in\mathcal{A}, i\neq j} \left(\sum_{m\in\mathcal{C}} x^{m}_{(i,t),(j,t')} - \sum_{n\in R} z^{n}_{(i,t),(j,t')} \right) + \sum_{m\in\mathcal{C}} c_m K_m \tag{1}$$

$$s.t. \quad \sum_{(i,t),(j,t')\in\mathcal{A}\cup\mathcal{A}'} z^{n}_{(i,t),(j,t')} - \sum_{(j,t'),(i,t)\in\mathcal{A}\cup\mathcal{A}'} z^{n}_{(i,t),(j,t')} = \begin{cases} 1 & \text{if } (i,t) = (i_o, t_o) \\ -1 & \text{if } (i,t) = (i_o, t_o) \\ 0 & \text{otherwise} \end{cases}$$

$$\forall n \in \mathcal{R},\ \forall (i,t) \in \mathcal{N},\ \forall (j',t) \in \mathcal{N}' \tag{2}$$

$$\sum_{(i,t),(j,t')_{i\neq j}\in\mathcal{A}} x^{m}_{(i,t),(j,t')} - \sum_{(j,t'),(i,t)_{i\neq j}\in\mathcal{A}} x^{m}_{(i,t),(j,t')} = \begin{cases} K_m & \text{if } (i,t) = (i_o, t_o) \\ -K_m & \text{if } (i,t) = (i_o, t_o) \\ 0 & \text{otherwise} \end{cases}$$

$$\forall (i,t) \in \mathcal{N}, m \in \mathcal{C} \tag{3}$$

$$\sum_{m\in\mathcal{C}} \sum_{(i,t),(j,t')\in\mathcal{A}, i\neq j} x^{m}_{(i,t),(j,t')} \leq c^{p}_{(i,t)}, \qquad \forall (i,t) \in \mathcal{N} \tag{4}$$

$$\sum_{m\in\mathcal{C}} \sum_{(j,t'),(i,t)\in\mathcal{A}, i\neq j} x^{m}_{(j,t'),(i,t)} \leq c^{d}_{(j,t')}, \qquad \forall (i,t) \in \mathcal{N} \tag{5}$$

$$\sum_{n\in R} z^{n}_{(i,t),(j,t')} \leq \sum_{m\in\mathcal{C}} x^{m}_{(i,t),(j,t')}, \quad \forall (i,t),(j,t') \in \mathcal{A}, i \neq j \tag{6}$$

$$x^{h}_{(i,t),(j,t')} = 0, \qquad \forall i \neq j \cup (i,t),(j,t') \in \mathcal{L} \tag{7}$$

$$z^{n}_{(i,t),(j,t')} = \{0,1\}, \quad \forall n \in \mathcal{R}, (i,t),(j,t') \in \mathcal{A} \cup \mathcal{A}' \tag{8}$$

$$x^{m}_{(i,t),(j,t')} \in \mathbb{Z}_{\geq 0}, \qquad \forall (i,t),(j,t') \in \mathcal{A} \cup \mathcal{A}' \tag{9}$$

The objective of the model, expressed in (1), is minimizing the sum of truck operating cost, container late penalty cost, and the purchase cost of two types of trucks. The objective function also includes the energy saving of empty trucks in our system. The first term expresses the total travel cost of truck flow. The second term shows the penalty cost, which incurs if a container is picked up earlier than its earliest pickup time, and/or delivered later than its latest delivery time. The third term captures that if a truck is not loaded on an arc, then the incurred cost will be lower than if loaded. Here we assume the cost difference is the same no matter whether it is on a moving arc or on a waiting arc. The resulting cost reduction should be subtracted, as in the first term $c^m_{(i,t),(j,t')}$ is the unit cost for a loaded truck. The last term is the truck depreciation cost on a per day basis.

In terms of constraints, constraint (2) specifies container flow conservation, for each container n in the network. The constraint encompasses both real arc and auxiliary arc, to ensure that every container goes out of the time-expanded network when it is delivered. Constraint (3) specifies truck flow conservation, which is subject to the initial truck distribution. Note that the start node (i_0, t_0) is different from the one in constraints (2). We use dummy depot for all the trucks on duty. Constraint (4) is about terminal capacity for trucks to pick up containers. Constraint (5) is about terminal capacity for trucks to deliver containers. These capacity constraints should be satisfied at each time point. These constraints only include travel arcs since trucks are allowed to queue at each terminal. Constraint (6) ensures that there are always enough trucks to move containers on any arc $(i, t), (j, t')$. The constraint also encompasses truck relocation. Constraint (7) is the off-duty constraint that drivers of conventional trucks have their rest or lunches. Constraint (8) shows that all the $z^n_{(i,t),(j,t')}$ variables are binary variable. Constraint (9) stipulates non-negativity for all integer variables $x^m_{(i,t),(j,t')}$.

Results from the qualitative part of the study

Text analysis

Responses of interviewees, when transcribed, yielded a total of 38,640 words consisting of 6,418 distinct words. Table 4 presents relevant statistics for the transcripts grouped under each of the three topical areas.

Table 4. Word counts of transcripts

Topical area	Words	Distinct words
Current issues	8,878	1,719
Drayage automation	19,449	2,756
Impacts	10,313	1,943
Total	38,640	4,257

The analysis of the word usage identified the 30 most frequently used words shown in Table 5. While it is not surprising to find some of these words, such as “truck/trucks”, “automation/autonomous”, “driver/drivers”, “freight”, “technology” and other terms that are closely associated with the main topics of the interviews, presence of terms such as “system/systems”, “data”, “safety”, “traffic”, “infrastructure,”, “labor”, and is illustrative of the issues that frequently came up during the interviews. On the other hand, the absence of “regulation” is somewhat of a surprise. In terms of governments, “city” is mentioned 56% more frequently than “state”, suggesting the importance of municipality as an actor, along with “company/companies”, “industry”, and “business”, in the automation conversation. Another noteworthy point is the absence of “distribution centers” or “warehouses” in contrast to the presence of “port” and “terminal/terminals” in the top 30. This may suggest that interviewees see intermodal facilities such as ports and rail yards as providing the most obvious application opportunities for ADS. Finally, it is surprising to find no words related to “cost” or “efficiency” in the list.

Table 5. Frequently used words

Word	Frequency	Rank
truck/trucks	268	1
system/systems	116	2
driver/drivers	96	3
automated/autonomous	81	4
company/companies	79	5
industry	71	6
trucking	71	7
terminal/terminals	71	8
data	69	9
technology	67	10
vehicle/vehicles	61	11
automation	59	12

time	59	13
port	52	14
safety	51	15
container	48	16
city	47	17
traffic	45	18
people	43	19
road	39	20
drive/driving	38	21
infrastructure	36	22
freight	33	23
labor	32	24
rail	30	25
state	30	26
operators	26	27
operations	25	28
business	22	29
Drayage	21	30

Collocation analysis identifies pairs of words that appear frequently in a close proximity using a statistical test. The words shown in the following tables are those that appear within 12 words before or after the target word at a statistically significant (95% significance level) frequency. The likelihood indicates the strength of evidence for each word. The collocation analysis was performed separately for three transcripts, categorized into: current issues in drayage for the local region of the respondent (Current Issues), prospects and issues related to drayage automation (Drayage Automation), and expected impacts of automated drayage (Impacts). In collocation analysis, a target word must be selected. We tried numerous words, typically starting from modal verbs and expanding to nouns and adjectives. Pronouns, articles, and words that are too generic to provide specific interpretation were excluded from the results shown below.

Table 6 shows the results of the collocation analysis of the transcripts associated with Current Issues. The results clearly indicate traffic congestion as a major concern. Also, relocation of terminals and need to improve infrastructure seem to be discussed as issues of concern. That being said, exact contexts in which these words were used during the interviews must be interpreted from the actual reading of the transcripts.

Table 6. Collocation analysis of discussion of current issues

	Word	**Frequency**	**Likelihood**
Target word = improve"	bridges	1	9.75
	roadways	1	9.75
Target word = "issue/issues"	congestion	7	24.4

Target word = "terminal/terminals"	relocated	5	21.2
	delays	4	18.4

The analysis of the discussions related to feasibility, opportunity, and challenges associated with drayage automation, shown in Table 7, produces a number of statistically significant results. In general, the results show that interviewees expressed positive opinions on drayage automation. Words related to improved performance such as “quality”, productivity”, “performance” are mentioned with positive target words. On the other hand, a large retail company is mentioned with the target word “less”. A concordant analysis is performed for the word “amazon” to extract discussions in which the word is mentioned (see Appendix). In all instances, “amazon” is mentioned as one of the actors that may push for automation. But, some interviewees felt that the last-mile delivery is many years away from actual implementation. Some interviewees mentioned labor organizations as potential challenges toward automation of drayage.

Table 7. Collocation analysis of discussion of drayage automation

	Word	**Frequency**	**Likelihood**
Target word = "better"	precision	3	25.8
	driven	3	25.8
	discipline	3	25.8
	eliminated	3	25.8
	overall	3	19.0
	performance	3	17.3
	visible	2	15.5
	quality	3	14.9
	service	3	14.0
Target word = "more"	expensive	5	20.1
	expressway	3	18.7
	travel	4	18.3
	open	4	16.1
Target word = "less"	amazon	3	15.4
	delivery	3	14.1
Target word = "help"	trade	2	14.1
	productivity	2	14.1
	implementation	2	14.1
	decisions	2	12.5
Target word = "may"	teamster	3	17.6
	unions	4	16.9
Target word = "reduce*"	payouts	3	33.0
	risk	3	24.4
	ownership	2	20.2

*Indicates a wildcard expression used for search

Table 8 shows the results of collocation analysis of the discussions of the potential impacts of middle-mile automation. Again, interviewees generally discussed positive impacts of automation. A major theme seems to be the potential for improving safety and productivity through better utilization of data with better quality and quantity.

Table 8. Collocation analysis of discussion of impacts

	Word	Frequency	Likelihood
Target word = "better"	utilize	3	19.9
	informed	2	14.5
	loads	3	13.4
Target word = "more"	customers	4	16.2
	asset	4	16.2
	companies	9	14.6
Target word = "less"	active	4	26.0
	people	5	13.9
	exposed	2	13.0
Target word = "fewer"	workers	4	24.8
	children	2	16.8
	environment	2	14.0
	road	3	11.5
Target word = "improve*"	safety	4	12.6
Target word = "data"	volume	4	26.1
	accurate	3	17.7
	trip	3	17.7
	quality	5	16.8
	share	3	13.5

*Indicates a wildcard expression used for search

The text analysis outlined in this section provides a peak into the trends and themes in interviewees' responses. The next section discusses insights obtained from detailed reading of the transcripts.

Interpretation and key insights

This section discusses information and insights shared by the interviewees. The discussion is organized in three main areas: current status and issues facing drayage, prospects for middle-mile automation, and the path to pilot testing.

The drayage industry

While middle-mile is the term used to describe short-distance movements, mostly of containers, between freight facilities, its actual operation and the industry depend heavily on local conditions. In freight hubs like Chicago and Los Angeles, the drayage industry encompasses the movement of goods between ports and intermodal facilities. A container coming from the west coast may arrive in one Chicago yard by train, then be drayed via truck to another yard, where it will resume its journey east. The drayage industry is characterized by a mixture of company sizes. Some interviewees estimated that about half of drayage trips are taken by small or individual operators, and the other half by large companies with fleet sizes in the hundreds. Others put the ratio of trips at ⅓ owner-operators, ⅓ small companies, and ⅓ large companies. Interviewees noted a difference in the trips taken - large companies operate databases, have reputations and contacts, and can coordinate trips, giving them an advantage on securing the most profitable contracts. **Small operators are then left to fill in gaps in the system, taking trips which are less profitable or involve worse conditions.**

Interviewees discussed hours-of-operation standards for drivers as an opportunity for ADS. Human drivers are restricted to only driving a certain number of hours in the day for safety reasons. ADS would have no such limitations and could operate around the clock. However, **most problems in the contemporary supply chain are not the kind which ADS could address.**

Congestion is an issue for drayage operations. With truckers paid by the mile or per haul rather than the hour, time spent sitting in congestion represents a potentially disastrous loss in revenue, in addition to slowing down the movement of goods. Interviewees felt that replacing human-operated vehicles with autonomous vehicles would not impact the level of congestion, for both trucks and passenger vehicles, as they would still take up space.

Another issue in contemporary trucking is a lack of technicians trained to deal with new technology. One interviewee cited a diesel technician shortage as the largest issue in trucking following the widely-discussed trucker shortage. If technicians capable of maintaining the existing fleet are already in high demand, **maintenance of ADS enabled trucks would require even more specialized training and would only exacerbate the problem**. This has also troubled the adoption of zero-emission vehicles such as battery- or hydrogen-powered trucks. Others discussed shortages of drivers, ship/barge pilots, and other necessary positions for the movement of goods. The ability of automated systems to alleviate the labor shortage across the supply chain without increasing costs or worsening safety outcomes will be crucial in its adoption.

Some interviewees felt that the major opportunities for drayage within the next decade did not involve ADS, looking instead to “big data,” or the adoption of increasingly sophisticated tracking and routing algorithms and the communication between carriers as offering significant efficiency gains. One of the oldest problems in drayage that companies and technologies have been working to ameliorate for decades is the “empty container” phenomenon, when drivers have no choice but to transport an empty container or even an unloaded chassis due to an inefficient allocation of trucks. Interviewees explained this as an issue which could be ameliorated but likely never “solved.” **The addition of ADS to the chain without any other changes would lead to the empty containers and chassis being moved by ADS rather than humans, not addressing the underlying issue.**

Finally, interviewees mentioned the aging workforce in trucking, skewing older than most careers. A large number of supply chain workers fall into the 45-54 age range and older, and interviewees felt they would be reluctant to adopt new technologies, citing cabin-facing cameras as a major source of contention. Working with automated vehicles as a safety driver (mandated requirement in many states, with California requiring two safety drivers), maintenance tech, inspector, yard operator, or other role may be unappealing to this workforce, and some interviewees predicted that they would need to age out of the supply chain before mass adoption of new technology could happen.

Specific for the Chicago metropolitan region, the drayage environment is unique when compared with the rest of the United States for several reasons which could impact the adoption of ADS. Interviewees noted Chicago's high congestion and need for drayage between intermodal yards. ADS in theory can operate during times of lower congestion when truckers may be legally barred from driving, making it suited to avoiding a major problem in Chicago drayage. However, interviewees stated that ADS has not yet been proven capable of operating without a human driver in congested conditions.

The Chicago metropolitan region has as many as 19 intermodal yards, though fewer are currently active. Because of Chicago's status as a major rail hub, these yards generate a large amount of trucking traffic between them. That traffic contends with and contributes to congestion in the region. This is not a problem that interviewees felt could be solved by ADS - whether the trucks are driven by humans or are automated, the traffic between the yards will be the same.

Automation in drayage

According to interviewees, for new technologies to see mass adoption in drayage, they will need to have a demonstrable impact on safety and/or cost.

Conditions for adoption

Multiple interviewees mentioned the safety database maintained by the USDOT. All trucking operators in the United States have their safety and inspection records publicly available for potential employers to view. Because of the large number of operators competing for contracts, any driver who has even a middling safety record will find employment difficult. The impacts on automation adoption are twofold. First, **the makers of ADS will need to prove that they can match or best human operators in safety and passing inspections, conclusively**, before operators will begin purchasing and using ADS. Second, if this is proven to the satisfaction of operators and insurance companies, it may lead to adoption if other conditions such as return on investment are met.

Many interviewees held the opinion that **the moment ADS could be proven to lower costs without impugning safety, mass adoption would follow**. **However, many interviewees felt that tipping point to be further away than ADS companies believe.** The costs associated with manufacturing ADS-equipped vehicles make them much more expensive than similar non-ADS trucks. The promise of automating trucks is labor savings, but **there are not many instances in which contemporary ADS-enabled trucks can safely operate without a human present for various reasons**.

One interviewee pointed to the disparity between where ADS is tested and where it would need to operate to become an integral part of the drayage ecosystem. Tests currently take place in the Sun

Belt, especially on a route between Texas and California - benefitting from long sightlines and clear, sunny weather. The vast majority of long-distance and middle-mile trips - the areas ADS would likely compete in first - involve some amount of inclement weather, unpredictability, and darkness. The latter is especially important to consider because one of the major promises of ADS is that it will free operators from hour-of-operation regulations, allowing trips around the clock, or concentrated at nighttime to avoid congestion. ADS will need to prove it can function in adverse conditions without safety drivers before operators will begin purchasing ADS vehicles.

Humans can also react to new or unexpected situations, whereas ADS can only react within its programmed parameters. One interviewee gave automation in intermodal yards as an example. When there are no problems, automation can save money and work more efficiently than humans. However, if a problem does arise, experienced human laborers are necessary to solve it. When a truck breaks down, it needs to be taken to a repair facility and the load has to be transferred to a different vehicle or a different tractor must take over so that the shipment can reach the destination in a timely manner. Interviewees pointed out that automating responses to cope with unexpected events is not possible in the near future. **Interviewees generally thought it unlikely that the entire workforce in the supply chain, or in trucking, would be replaced by automation** though they differed on the amount that could be replaced, and how quickly the change would happen.

Legal and labor barriers

If ADS can demonstrate cost and safety advantages, **it would still need the regulatory environment to change** before it becomes possible to use beyond tests and pilots. Many jurisdictions explicitly require humans to be present in a vehicle for operation, either as drivers or “safety drivers.” This can also be implicit in other requirements - the purview of a truck driver extends beyond driving, into many skills which are harder to replace. One interviewee discussed how ADS trucks cannot tighten their own screws, file their own paperwork, examine their own chassis, etc. As vehicle inspections will be as necessary, or more, with the advent of ADS, ADS companies must find a way to address these concerns without compromising on their promise of labor savings.

Other regulatory barriers may be simpler to overcome. ADS-equipped trucks could save on manufacturing costs if regulations requiring seats, brake pedals, steering wheels, etc. could be rescinded, or ADS granted an exception. The NHTSA is already examining changes to these regulations, and interviewees felt that if the trucking industry were to join ADS companies in pushing for change, it would happen rapidly. The trucking industry represents a significant amount of economic activity in the United States, and a crucial link in the supply chain, giving it political leverage.

Interviewees also discussed how insurance companies are responding to ADS. **Many are adding surcharges to automated vehicles, even ones with safety drivers, due to a lack of performance data.** One interviewee stated that three to five years of data from ADS trucks operating in real-world conditions, including in the environments that are challenging for the technology, will be needed before the insurance companies feel confident in the technology. The uncertainty surrounding the performance of ADS on public roads makes insurance companies cautious, which in turn prevents the use of ADS and the generation of performance data, resulting in a vicious cycle. Some interviewees felt that governments can play a role in the development and testing of ADS trucks to generate necessary data for the insurance companies to determine the appropriate rates to charge with more confidence.

Litigation is another concern for both truck drivers and fleet operators. Multiple interviewees cited fears of frivolous lawsuits affecting operators, claiming that juries are biased against truck drivers. This bias, they feared, would be even more pronounced in the event of a crash involving ADS. Fleet operators would be hesitant to adopt ADS if it opens them up to risk in court. Liability for crashes involving ADS has not been standardized. Fleet operators are only sometimes liable for damages in courts currently, depending on the behavior of the truck driver. Driver-monitoring technologies, such as cab-facing cameras, are being embraced by many drivers and operators for this reason. **If operators are liable for every crash involving ADS, that is a reason to retain human drivers unless the technology can significantly lower crash rates.**

Interviewees predicted organized pushback against ADS from labor unions, specifically the Teamsters. These unions are already organizing to retain human drivers in ADS trucks, citing safety concerns. As labor cost savings are a major promise of ADS, and would be necessary to offset the increased purchase and maintenance costs of the technology, the only path to profitable adoption by fleet operators puts them at odds with their human workforce and the unions. Interviewees expected that unions would push back in both the workplace and politically. However, many stated that if ADS were able to improve safety and lower costs, the unions would not be able to stand in the way of mass adoption and would be relegated to seeking compromises to retain fractions of the current workforce. One interviewee reflected on the need to train a younger workforce of truck drivers as being very important.

One interviewee discussed a conscious strategy of divorcing environmentalism from automation. If the two were linked, unions may begin to oppose "green" policies out of fear of losing employment. ADS companies have previously sought to tie the two ideas together to promote their technology. If that remains the case as automation sees wider adoption, environmental policies that do not explicitly separate themselves from automation may see pushback.

Testing and pilot projects

Interviewees agreed that **more testing on a larger scale than current tests would be necessary before ADS could be adopted widely**. Many interest groups want more information about how ADS operates and what it can do. Interviewees cited insurance companies who need safety data before they will be willing to lower premiums; fleet operators who want proof of safety and cost reduction before purchasing ADS-equipped trucks; and politicians and the general public who will desire proof of ADS's safety before allowing it on public roads.

However, interviewees identified issues in establishing tests and pilot projects. Without proof of safety, jurisdictions will likely not allow ADS to pilot on public roads. Private roads at the scale needed to thoroughly test ADS are difficult to find, and some regulations also apply on private property. **Interviewees felt that significant public support would need to exist before testing could begin.**

Interviewees identified areas where ADS needs to prove its effectiveness. Roads with steep slopes, tight turns, and low visibility; dark skies; inclement weather, including rain, snow, and black ice; congested roads; and other adverse conditions which trained human drivers can currently operate under, but which ADS cannot. Interviewees argued that pilot programs should conclusively address these concerns before ADS can be allowed into the supply chain. The public and fleet operators would feel the same, though for different reasons.

Other concerns

One interviewee discussed a disconnect in the audience of ADS. ADS companies are addressing their promotional material at venture capital firms, as most are not publicly traded and rely on investors to continue research and development. However, to become publicly traded, they will need to prove the value of ADS to the fleet operators who would purchase it. This focus on venture capital means that tests are intended to make ADS look impressive. Different types of testing will be needed to prove the technology to fleet operators so that they may consider purchasing ADS - for instance, tests on sunny Arizona roads do not prove how ADS would handle driving through a snowstorm in Minnesota. **ADS developers will need to change their approach if they are to court fleet operators.** However, with the funding for research currently coming from venture capital, that change is not possible for many companies to make yet. As mentioned earlier, the governments and universities may have a role to play in filling this gap.

Another concern interviewees shared relates to safety, namely the “first big crash.” If ADS sees mass adoption on public roads, they felt that eventually there would be an expensive, high-profile crash involving ADS, after which fleet operators, the public, and the market in general, would sour on ADS for a significant period of time. They supported this claim by citing a recent high-profile crash in California involving a lithium-ion battery vehicle, resulting in doubts about the state’s zero-emissions goals. Vehicle automation itself had its “first big crash” in 2018, when an Uber ADS-equipped car killed a woman in Arizona. After the crash, venture capital funding decreased and Uber divested from ADS research, and it is still discussed as a setback in the field (Smiley, 2021). Interviewees felt that something similar would be on the horizon once ADS-equipped trucks began operation on public roads.

Full automation and self-driving are not the only ways that automation technology can enter the supply chain, and some interviewees saw **more potential in the adoption of limited automation**: automated emergency braking, for instance, as well as lane detection, inebriation detection, and others. These interviewees said that these technologies are already proven to increase safety and are already seeing adoption, or even being required in new vehicles in some jurisdictions. This limited automation already exists, already has proven itself, and is significantly simpler to develop and adopt than full self-driving vehicles. Because of the safety benefits of limited automation, some interviewees felt that it would slow down or even prevent the adoption of full self-driving technology, making it less urgent by improving safety while retaining a human workforce.

One interviewee discussed that the initial introduction of ADS to the middle mile of the supply chain may see a short-term loss of efficiency while the national trucking fleet is mixed between self-driving and human-operated vehicles. This would become an overall efficiency improvement once the majority of vehicles were replaced by ADS. One possible advantage of adopting ADS for drayage is the possibility of designing the vehicle specifically for short-distance movements. As ADS trucks will likely be battery powered, increase in tare weight, and thus reduction in the load capacity, is a serious concern. If ADS trucks with smaller batteries can be developed specifically for short-distance travel, it may interest some fleet owners. This idea, however was refuted by some of the interviewees. They argued that vehicles used for drayage are typically the oldest and least efficient because the industry is arguably the least profitable of all trucking, and it is unlikely that drayage companies will invest in purchasing new and presumably expensive trucks.

Interviewees agreed that if ADS could prove itself to have cost and safety improvements, large operators would be faster to adopt ADS-equipped trucks into their fleets than smaller ones. This is partly because of the greater capacity for large fleet operators to plan and coordinate purchases and operations. Smaller operators lack capital and must attempt to break even by purchasing older, used trucks and running them for as long as possible, often on less profitable routes. Some interviewees predicted that **there would need to be significant fleet turnover generating a "used ADS" market before smaller operators could begin adopting the technology**. They cited electric vehicles as demonstrating a similar pattern of adoption. Interviewees predicted that the adoption of ADS would favor larger, established companies, increasing their market share, and creating a feedback loop as larger companies saw cost and safety benefits before smaller ones. One interviewee predicted that the smallest participants in trucking, the owner-operators, may disappear completely.

Cybersecurity was cited as a concern by some interviewees, though no interviewee claimed it as an area of expertise. Many agreed that cybersecurity issues with ADS would only become worthy of investigation if ADS companies could first prove cost savings and safety increases from their technology - essentially, that cybersecurity would not receive attention until the technology first became viable for adoption.

Interviewees generally held that the mass installation of "smart" infrastructure and V2I communication was similarly far into the future. If governments could not afford or were not willing to invest in maintaining existing infrastructure, or developing it to reduce congestion, they felt that the expensive prospect of overhauling the infrastructure to become capable of real-time communication was even further into the future. This implies that initial adoption of ADS would have to happen without the support of smart infrastructure, and that it would only see investment if ADS were already operating on the roads.

Results from the quantitative part of the study

Setup

We consider a set of instances with 17 terminals that belong to the six Class 1 railroads (BNSF, CSX, Canadian Pacific Kansas City, Norfolk Southern, Canadian National, and Union Pacific). Each instance has 800 containers to be transported between two terminals that are owned by different railroads, with an operation time of eight hours. The eight-hour operation time is discretized into 48 time intervals, each lasting 10 minutes. The predicted travel times between terminals, obtained from Google Maps on a Monday, are listed in Table 9. In Table 9, the terminals are labeled as A, B, C, D, etc. The specific locations of the terminals can be found in Figure 4. Some off-diagonal cells in Table 9 are labeled as "\", as they correspond to terminal pairs where the two terminals belong to the same railroad. The schedule for each container is randomly generated within the given time horizon. The capacity for both pickup and delivery at each terminal is set to 15 trucks per 10 minutes.

Table 9. Travel time between terminals (in 10 minutes)

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q
A	\	\	\	\	4	4.5	4	3	2.5	2.5	2	2.5	3	3.5	2	5.5	4
B	\	\	6	3	3.5	4.5	5	3.5	1.5	2.5	1.5	2	2.5	2.5	3	5.5	3
C	\	7	\	6	6	3.5	8.5	7.5	7	6.5	6.5	6.5	6.5	7.5	6.5	2.5	6
D	\	2	2	\	2.5	3	3.5	2.5	3	1.5	2	2.5	3	3	1.5	4	2.5
E	4	4	4	4	\	\	5.5	4.5	3	3	2.5	2.5	2	3	3.5	3.5	1
F	4.5	4.5	4.5	4.5	\	\	6	4.5	4.5	4.5	4	4	4	5	4	1.5	3.5
G	3	4	6	3	3	4.5	\	\	4.5	4	3.5	4	4.5	5	1	6	4.5
H	3	3.5	6	3	3	4.5	\	\	3.5	4	3	3	4	4.5	1.5	5.5	4.5
I	2.5	1.5	6	2.5	2.5	4.5	5.5	4	\	\	1	1	2	1.5	4	5.5	2.5
J	2.5	2.5	6	2.5	2.5	4.5	5.5	4.5	\	\	2.5	3	4	2.5	3.5	5.5	4
K	2	2	5.5	2	2	4	4.5	3	1	2.5	\	\	\	\	2.5	5	2
L	2.5	2	6	2.5	2.5	4.5	5	3.5	1.5	3	\	\	\	\	3	5	2.5
M	3	2.5	5.5	3	3	4	5.5	4	2	3.5	\	\	\	\	3.5	4.5	1.5
N	3.5	2.5	6.5	3.5	3.5	5	6	5	1.5	2	\	\	\	\	4	5.5	3
O	2.5	3.5	5.5	2.5	2.5	4	2	1.5	4.5	3	3	3.5	4	4	\	\	\
P	5.5	5.5	1.5	5.5	5.5	2	7	6	5.5	5	5	5	4.5	5.5	\	\	\
Q	4	3	5	4	4	3.5	5.5	5	2.5	3	2	2	1.5	3	\	\	\

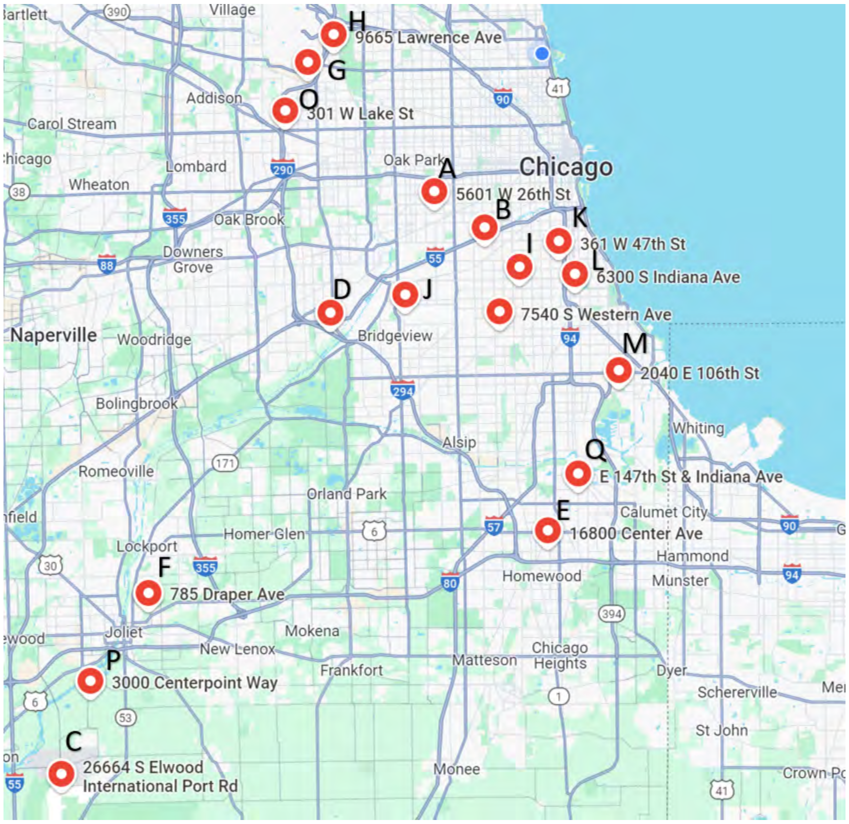


Figure 4: Locations of the 17 terminals in the Chicago metropolitan region

We consider that a conventional truck has a driver onboard, who can work seven hours in a day and has a one-hour off-duty lunch break (which is equivalent to six time intervals). Consequently, we introduce the lunch time arc set $\mathcal{L}$. The parameters used in this section are listed in Table 10. Note that the difference in truck depreciation cost is based on the difference of purchase price of an autonomous truck and a conventional truck. We assume that the purchase price of an autonomous truck is $180,000 and a conventional truck to be $135,000. A service life of 12 years, a discount factor of 5%, and 365 days of operation per year are further assumed in calculating the depreciation cost. Alternatively, it can be viewed as the depreciation cost of purchasing an ADS which is then installed on a conventional truck.

Table 10. Parameter values

Parameter	Description	Value and unit
$c^a_{(i,t),(j,t')}$	Unit cost of an autonomous truck on moving arc $(i,t),(j,t')$	$3.59/10 min
$c^h_{(i,t),(j,t')}$	Unit cost of a conventional truck on moving arc $(i,t),(j,t')$	$7.75/10 min
$c^a_{(i,t),(i,t')}$	Unit cost of an autonomous truck on waiting arc $(i,t),(i,t')$	$0.16/10 min
$c^h_{(i,t),(i,t')}$	Unit cost of a conventional truck on waiting arc $(i,t),(i,t')$	$0.52/10 min
c^p_i	Terminal capacity of pickup	15 trucks
c^d_i	Terminal capacity of delivery	15 trucks
$p^n_{(i,t),(j,t')}$	Penalty of early pickup and late delivery	Twice the arc cost

c_a	Truck depreciation cost: autonomous truck	$55.64/day
c_h	Truck depreciation cost: conventional truck	$41.73/day
τ	Length of a time interval	10 minutes
s	Fuel cost difference for a moving truck: empty vs. loaded	$2.15/10 min

Sources: Burnham et al. (2021), Noruzoliaee et al. (2021), Argonne National Laboratory (2015), Mihelic et al., (2023), and Durabak (2021).

Results

We report results from solving the optimization model for four cases. In case 1, we examine the performance of drayage operations with varying fleet sizes of conventional trucks. In case 2, we determine the fleet size of conventional trucks as part of the drayage operation optimization. In case 3, we fix the fleet size at the optimal fleet size from case 2, and investigate the performance of drayage operations with a range of autonomous truck penetration rates. In case 4, we seek the optimal fleet size if the entire fleet becomes autonomous. All the cases are solved by Gurobi version 9.5.2, on a PC with a 3.0 GHz CPU and 16.0 GB RAM.

Case 1: Different fleet sizes with only conventional trucks

In this case, since only conventional trucks are considered, $\mathcal{C}$ ={conventional truck}, i.e., there is only one $m = 1$ in the model formulation. We solve the optimization under four fleet sizes: $K = 20, 30, 40$, and 50 drayage trucks. Table 11 reports the system total cost, container time related cost, truck operating cost, and truck depreciation cost. The system total cost and cost breakdown are further visualized in Figure 5. We can see that that the system total cost first decreases as the number of trucks increases. A larger fleet size can better accommodate the demand for container movement. Thus, container time cost keeps decreasing. On the other hand, truck operating cost and depreciation cost follow an increasing trend. The best tradeoff between container cost and truck cost is reached at a fleet size of 30, where the system total cost reaches the minimum. This suggests that the optimal fleet size may be between 30 and 40 trucks.

As we continuously increase the fleet size, the cost reduction from more efficient container movement is not large enough to offset the concurrent increase in truck related cost associated with added fuel, maintenance, and ownership expenses. It is also interesting to observe that at the fleet size of 50, truck operating cost is actually slightly decreased compared to the case with 40 trucks, which may be attributed to reduced empty relocating truck travel. However, the cost reduction is small vis-à-vis the increase in truck depreciation cost. The container time cost reduction is also quite small, suggesting that a fleet of 40 trucks is good enough to move the containers. Adding more trucks does not help much in reducing the time penalty of containers. Overall, the system total cost is still increased, quite significantly from $26,937 to $27,400.

Table 11. System total cost and breakdown under different fleet sizes with conventional trucks (in $)

Fleet size	System total cost	Container time cost	Truck operating cost	Truck depreciation cost
20	27,292	22,030	4,335	927

30	26,907	18,960	6,557	1,391
40	26,937	16,358	8,724	1,855
50	27,400	16,365	8,716	2,318

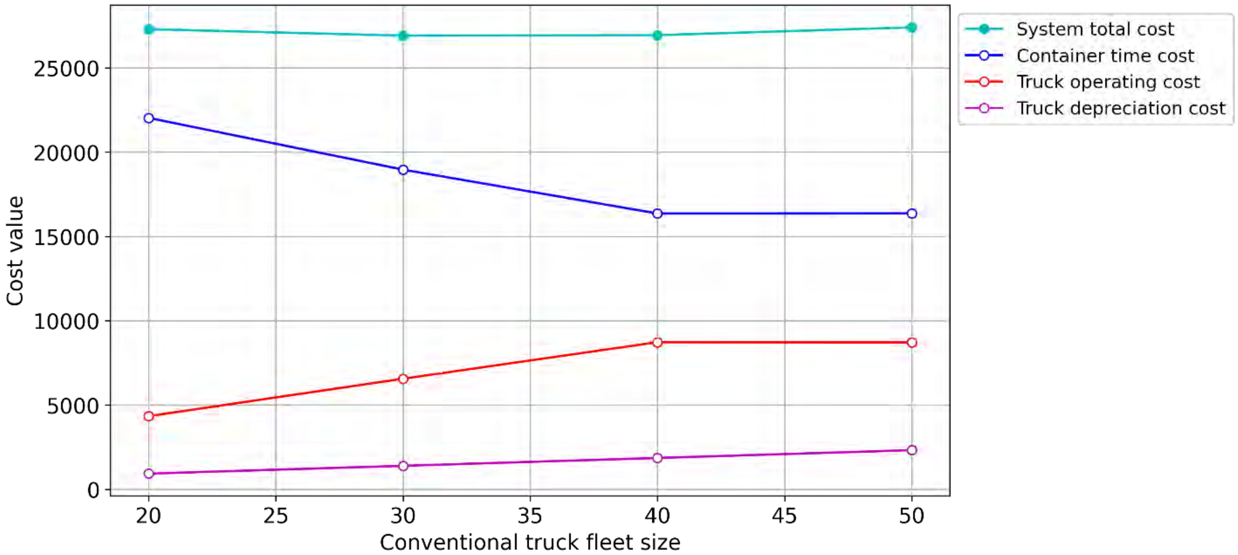


Figure 5: Cost values under different fleet sizes of conventional trucks ($)

Case 2: Optimal fleet size with only conventional trucks

In this case, again $\mathcal{C}$ ={conventional truck}, i.e., there is only one $m = 1$ in the model formulation. However, K are treated as a variable in addition to the x and z variables. Table 12 shows the result. Consistent with the conjecture from case 1, the optimal fleet size is 34, which is between 30 and 40. At this fleet size, the best tradeoff between container movement efficiency and truck cost (including both operating and depreciation costs) is achieved.

Table 12: System total cost and breakdown with the optimal fleet size of conventional trucks ($)

Fleet size	System total cost	Container time cost	Truck operating cost	Truck depreciation cost
34	26,888	17,893	7,423	1,577

Case 3: A mixed fleet of conventional and autonomous trucks

In this case, $\mathcal{C}$ ={conventional truck, autonomous truck}. So in the model formulation, $m \in \{1,2\}$, where 1 denotes conventional truck and 2 denotes autonomous truck. We consider a range of penetration rates for autonomous trucks, from 0% to 100%, while keeping the total fleet size fixed at the optimal fleet size when there are only conventional trucks. We consider this with the intent to capture that a drayage operator replaces – progressively and on a one-by-one basis – its conventional trucks with autonomous trucks. Seven autonomous truck penetration rates are examined, as shown in Table 13.

The results in Table 13, also visualized in Figure 6, clearly illustrate the benefit of adopting autonomous trucks in the drayage operation system, especially in terms of system total and container time costs. As the penetration rate of autonomous trucks increases, we observe a significant reduction in system total cost, from $26,887 at 0% autonomous truck penetration to $21,448 at 100% penetration, or 20% cost reduction. The container time cost follows a similar decreasing trend, dropping from $17,884 to $14,425, or 19.3% reduction, as the system moves from zero to full automation. This decrease is due to the improved operational efficiency using autonomous trucks, which can operate continuously without lunch breaks.

It is expected that autonomous trucks are electricity powered, which will be more energy efficient than diesel-powered conventional trucks. As a result, the combined truck operating cost of autonomous and conventional trucks continues to decline as the penetration of autonomous trucks increases. For example, at 0% autonomous truck penetration, the truck operating cost is $7,423. At 100% autonomous truck penetration, the truck operating cost is reduced to $5,137, or 31% reduction.

On the other hand, the truck depreciation cost increases as more autonomous trucks are introduced. This is primarily due to the higher purchase price associated with an autonomous truck than with a conventional truck. As autonomous technology becomes more mature and prevalent, the upfront cost is anticipated to reduce over time. Nonetheless, based on the current estimates, the upfront cost – realized in the form of truck depreciation cost – contribute non-trivially to the increase in the system total cost, which climbs from $1,576 at 0% penetration to $1,892 at 100%, or 20% increase.

Overall, the introduction of autonomous trucks enhances the chance that containers are picked up and delivered within their time windows, thus reducing the time penalty cost. In addition, due to more efficient energy use, the greater penetration of autonomous trucks reduces truck operating cost. Although autonomous trucks are more expensive than conventional trucks in upfront cost, these cost reduction benefits from having a more autonomous truck fleet overweighs the associated increase in depreciation cost. Thus, truck autonomation does offer an appealing option for drayage operations.

Table 13. System total cost and breakdown under different penetration rates of autonomous truck ($)

Autonomous truck penetration rate	System total cost	container time cost	conventional truck operating cost	autonomous truck operating cost	Truck depreciation cost
0%	26,887	17,884	7,423	0	1,576
18%	25,773	17,074	6,113	952	1,632
35%	24,756	16,490	4,800	1,876	1,688
50%	23,962	15,882	3,709	2,636	1,734
65%	23,183	15,415	2,618	3,368	1,780
82%	22,286	14,862	1,328	4,263	1,836
100%	21,448	14,425	0	5,137	1,892

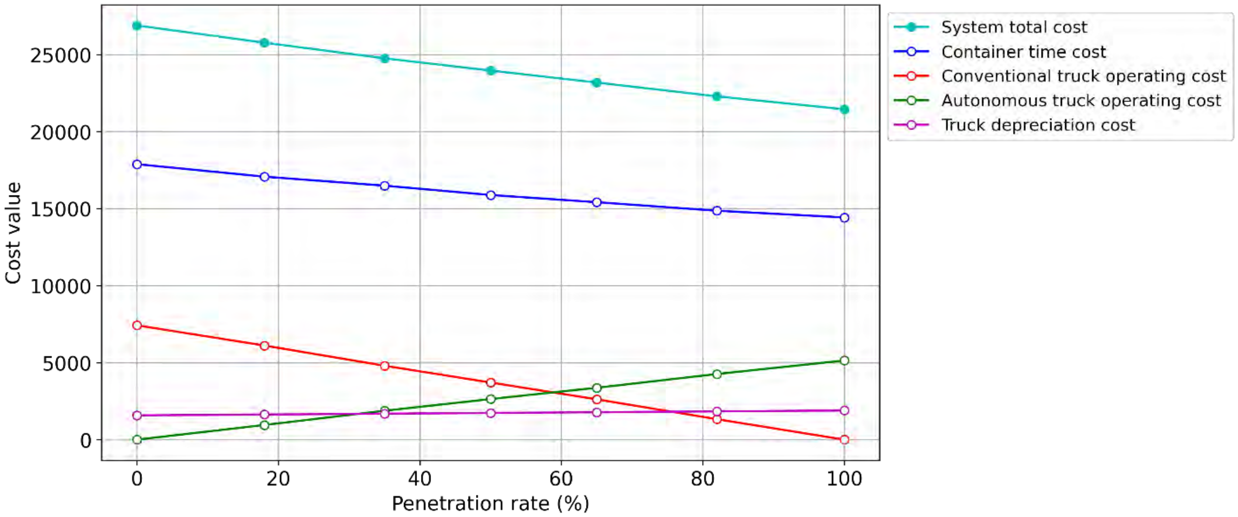


Figure 6: Cost values under different penetration rates of autonomous trucks ($)

Case 4: Optimal fleet size with only autonomous trucks

In the last case, we consider that the truck fleet is 100% autonomous. In the model formulation, $\mathcal{C}$ ={autonomous truck}, i.e., there is only one $m = 2$. The drayage operator further explores the possibility of adding more autonomous trucks to see if this helps reduce the system total cost even more. In doing so, an underlying assumption is that the drayage operator does not have a budget limit nor a depot parking capacity limit while determining the optimal fleet size of autonomous trucks. Nonetheless, these limits could be easily incorporated in the model.

Table 4 presents the results. First, we observe that the optimal fleet size is substantially greater than the optimal fleet size of conventional trucks – almost doubled, from 34 in Table 12 to 67. As a result, the truck operating and depreciation costs are significantly increased. On the other hand, the benefit of doing so is also manifested. Compared to case 2, container time cost decreases from $17,893 to $5,895, or a 67% decrease. The system total cost reduces from $26,888 to $19,268, or a 28% reduction. Even compared to the 100% autonomous truck scenario with a fleet of 34, as shown in case 3, the container time cost decreases from $14,425 to $5,895, which outweighs the increase in truck operation and depreciation due to a larger fleet. The system cost reduction compared to full autonomation but with a fleet of 34 trucks is still sizable, by 10%. Overall, having a larger autonomous truck fleet size is justified.

Table 14. System total cost and breakdown with the optimal fleet size of autonomous trucks ($)

Fleet size	System total cost	Container time cost	Truck operating cost	Truck depreciation cost
67	19,268	5,895	9,639	3,728

Extension - Lagrangian relaxation as a customized solution algorithm for the optimization model

While the integer programming model is solved using the commercial solver Gurobi, customized solution algorithms may be developed to potentially improve the solution efficiency, especially for large instances. Here, we suggest a Lagrangian relaxation-based solution approach as a possible direction to explore. In this section, our initial exploration of such a solution approach is presented. We first introduce the Lagrangian decomposition procedure to separate the original problem – which in the context of Lagrangian relaxation is termed the primal problem (PMP) – into two smaller subproblems. Then, a sub-gradient algorithm is applied to update the Lagrangian multipliers in an iterative manner. The whole structure of our algorithm and some preliminary results are presented lastly.

Lagrangian decomposition

The Lagrangian decomposition method has been widely applied to solve large scale problem by dividing them into several smaller subproblems. First, we denote that $X = \{x^m_{(i,t),(j,t')}\}_{(i,t),(j,t')\in\mathcal{A},m=\{1,2\}}$ and $Z = \{z^n_{(i,t),(j,t')}\}_{(i,t),(j,t')\in\mathcal{A},n\in\mathcal{R}}$. For simplicity, notice that a represents for autonomous truck and h represents for conventional truck. Hard coupling constraints (6) indicate the relationship between X and Z - the truck flow and the container flow. Thus, we relax this set of constraints and add it to the objective function (1) by introducing the set of Lagrangian multiplier $\mu = \{\mu_{(i,t),(j,t')} \geq 0\}_{(i,t),(j,t')\in A}$. In this way, we can write the relaxed objective function into following formulations:

$$L(\mu, X, Z) = \min \sum_{m\in\mathcal{C}} \sum_{(i,t),(j,t')\in\mathcal{A}} c^m_{(i,t),(j,t')} x^m_{(i,t),(j,t')} + \sum_{n\in\mathcal{R}} \sum_{(i,t),(j,t')\in\mathcal{P}_n} p^n_{(i,t),(j,t')} z^n_{(i,t),(j,t')}$$

$$-s \sum_{(i,t),(j,t')\in\mathcal{A},i\neq j} \left(\sum_{m\in\mathcal{C}} x^m_{(i,t),(j,t')} - \sum_{n\in\mathcal{R}} z^n_{(i,t),(j,t')} \right) + \sum_{m\in\mathcal{C}} c_m K_m$$

$$+ \sum_{(i,t),(j,t')\in\mathcal{A}} \mu_{(i,t),(j,t')} \left(\sum_{n\in\mathcal{R}} z^n_{(i,t),(j,t')} - \sum_{m\in\mathcal{C}} x^m_{(i,t),(j,t')} \right) \tag{10}$$

s.t. Constraints (1) - (5), (7) - (9).

In our problem, the variables $x^m_{(i,t),(j,t')}$ and $z^n_{(i,t),(j,t')}$ are only coupled in constraints (6). Therefore, by relaxing the coupling constraints (6), we can decompose the PMP into two subproblems that contain $x^m_{(i,t),(j,t')}$ and $z^n_{(i,t),(j,t')}$, respectively.

Sub-problem one (SP1): Minimum cost network flow problem

$$\Phi(\mu, Z) = \min \sum_{n\in\mathcal{R}} \sum_{(i,t),(j,t')\in\mathcal{P}_n} p^n_{(i,t),(j,t')} z^n_{(i,t),(j,t')} + \sum_{(i,t),(j,t')\in\mathcal{A}} \sum_{n\in\mathcal{R}} \mu_{(i,t),(j,t')} z^n_{(i,t),(j,t')}$$
$$+ s \sum_{(i,t),(j,t')\in\mathcal{A}, i\neq j} \sum_{n\in R} z^n_{(i,t),(j,t')} + \sum_{m\in\mathcal{C}} c_m K_m \tag{11}$$

s.t. Constraints (2) and (8).

SP1 is a minimum cost network flow problem with only the container flow conservation constraints. This problem can be solved to optimality by employing a shortest path algorithm, e.g., the label correcting method. When the subproblem is solved to optimum, the solution indicates that the containers are picked up once their earliest pickup time window opens. For simplicity, we denote the optimal solution of SP1 as $\bar{\bar{Z}}^k$, where k is the iteration counter.

Sub-problem two (SP2): Minimum cost network flow problem with resource constraints

$$\Psi(\mu, X) = \min \sum_{m\in\mathcal{C}} \sum_{(i,t),(j,t')\in\mathcal{A}_m} c^m_{(i,t),(j,t')} x^m_{(i,t),(j,t')} - \sum_{(i,t),(j,t')\in\mathcal{A}} \sum_{m\in\mathcal{C}} \mu_{(i,t),(j,t')} x^m_{(i,t),(j,t')}$$
$$- s \sum_{(i,t),(j,t')\in\mathcal{A}, i\neq j} \sum_{m\in\mathcal{C}} x^m_{(i,t),(j,t')} \tag{12}$$

s.t. Constraints (1), (3) - (5), (7) and (9).

SP2 is also a minimum cost network flow problem but with capacity constraints. A similar shortest path-based approach can be applied to solve the problem after adjusting the node capacity to link (arc) capacity. We use $\bar{\bar{X}}^k$ to denote the optimal solution of SP2. In this way, the lower bound is obtained by solving the two Lagrangian relaxed subproblems.

Obtaining an upper bound value

The most common way to obtain the feasible objective value - which is the upper bound value - is to plug $\bar{\bar{X}}^k$ and $\bar{\bar{Z}}^k$ into the PMP (Bektacs, 2010), (Liu, 2016). However, in our problem, the solution of SP1, $\bar{\bar{Z}}^k$, can be infeasible to PMP due to a limited number of trucks. Instead, we can only plug $\bar{\bar{X}}^k$ into PMP and solve the X_k fixed PMP to obtain the upper bound of the Lagrangian iterative process. Note that the optimal solution of SP2 is feasible to PMP since $\bar{\bar{X}}^k$ are subject to constraint (3).

Lagrangian relaxation-based algorithm

In the last section, we have stated the method to obtain upper bound. Our solution approach guarantees the optimal solution when the upper bound is equal to the lower bound according to the duality theory (Fisher, 1981). Otherwise, an iterative update of the value of $\mu_{(i,t),(j,t')}$ is needed to obtain a smaller gap between the upper bound and the lower bound. Thus, we apply a widely used standard subgradient algorithm to complete the iteration process.

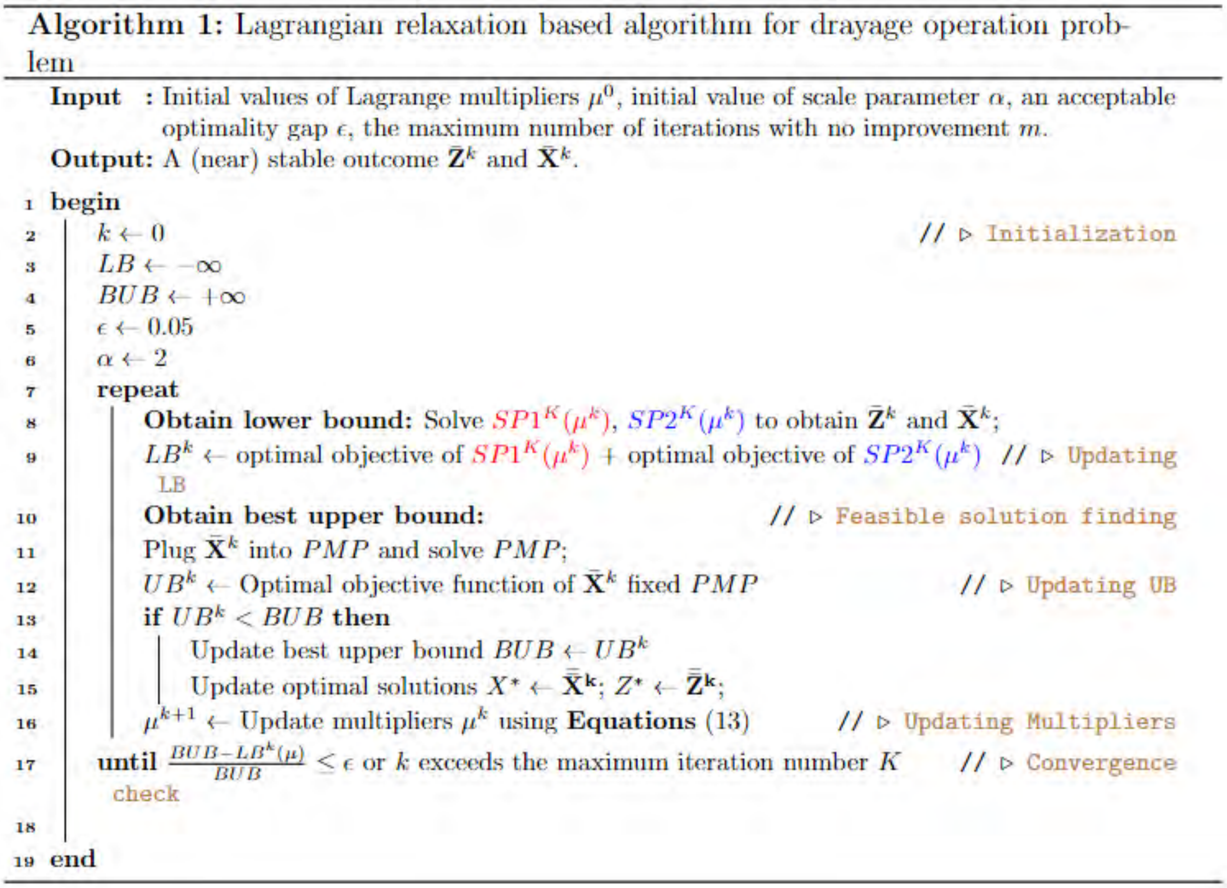
Lagrangian multiplier updating

Start with value of 0, the Lagrangian multiplier $\mu_{(i,t),(j,t')}$ is updated by equation (13).

$$\mu_{(i,t),(j,t')}^{k+1} = \max\left\{0, \mu_{(i,t),(j,t')}^{k} + \theta^k \left(\sum_{n\in R} z_{(i,t),(j,t')}^{n} - \sum_{m\in \mathcal{C}} x_{(i,t),(j,t')}^{m}\right)\right\} \tag{13}$$

where θ^k is the iteration step size calculated by equation (14). In (14), α is a parameter that we select between $(0,2]$. α initially starts at the value 2 and can be updated to $\frac{\alpha}{\beta}$, where β is a contraction ratio that is greater than 1. In the experiment, we use $\beta = 2$. The detailed algorithm is shown in Algorithm 1. BUB and $LB^k(\mu)$ are the best upper bound and the lower bound at kth iteration.

$$\theta^k = \frac{\alpha\left(BUB - LB^k(\mu)\right)}{\sum_{(i,t),(j,t')\in\mathcal{A}}\left[\sum_{n\in R}\left(z_{(i,t),(j,t')}^{n}\right)^k - \sum_{m\in\mathcal{C}}\left(x_{(i,t),(j,t')}^{m}\right)^k\right]^2} \tag{14}$$



Algorithm 1: Lagrangian relaxation based algorithm for drayage operation problem

Input : Initial values of Lagrange multipliers μ^0, initial value of scale parameter α, an acceptable optimality gap ϵ, the maximum number of iterations with no improvement m.

Output: A (near) stable outcome $\bar{\mathbf{Z}}^k$ and $\bar{\mathbf{X}}^k$.

```
begin
    $k \leftarrow 0$                                                         // ▷ Initialization
    $LB \leftarrow -\infty$
    $BUB \leftarrow +\infty$
    $\epsilon \leftarrow 0.05$
    $\alpha \leftarrow 2$
    repeat
        Obtain lower bound: Solve $SP1^K(\mu^k)$, $SP2^K(\mu^k)$ to obtain $\bar{\mathbf{Z}}^k$ and $\bar{\mathbf{X}}^k$;
        $LB^k \leftarrow$ optimal objective of $SP1^K(\mu^k)$ + optimal objective of $SP2^K(\mu^k)$  // ▷ Updating LB
        Obtain best upper bound:                                 // ▷ Feasible solution finding
        Plug $\bar{\mathbf{X}}^k$ into $PMP$ and solve $PMP$;
        $UB^k \leftarrow$ Optimal objective function of $\bar{\mathbf{X}}^k$ fixed $PMP$          // ▷ Updating UB
        if $UB^k < BUB$ then
            Update best upper bound $BUB \leftarrow UB^k$
            Update optimal solutions $X^* \leftarrow \bar{\bar{\mathbf{X}}}^{\mathbf{k}}$; $Z^* \leftarrow \bar{\bar{\mathbf{Z}}}^{\mathbf{k}}$;
        $\mu^{k+1} \leftarrow$ Update multipliers $\mu^k$ using Equations (13)       // ▷ Updating Multipliers
    until $\frac{BUB-LB^k(\mu)}{BUB} \leq \epsilon$ or $k$ exceeds the maximum iteration number $K$   // ▷ Convergence check

end
```

Preliminary results

We test a total of 100 container instance with the proposed Lagrangian relaxation-based algorithm. In this experiment, the parameter settings of Lagrangian relaxation algorithm are set as follows. We initially set parameter $\alpha = 2$ and decrease it based on the convergent tendency. The terminating parameters in the algorithm (line 17) are set to $\epsilon = 10^{-3}$ and $K = 2000$.

As shown in Figure 7, the initial rapid decrease in the upper bound and steady increase in the lower bound highlight the algorithm's capability to quickly improve solution quality and rigorously explore the solution space. The eventual convergence of the two bounds by the end of the iterations indicates that the algorithm is able to find a near-optimal solution. Future investigation may extend to large problem instances, to further understand the scalability of the Lagrangian relaxation-based solution approach.

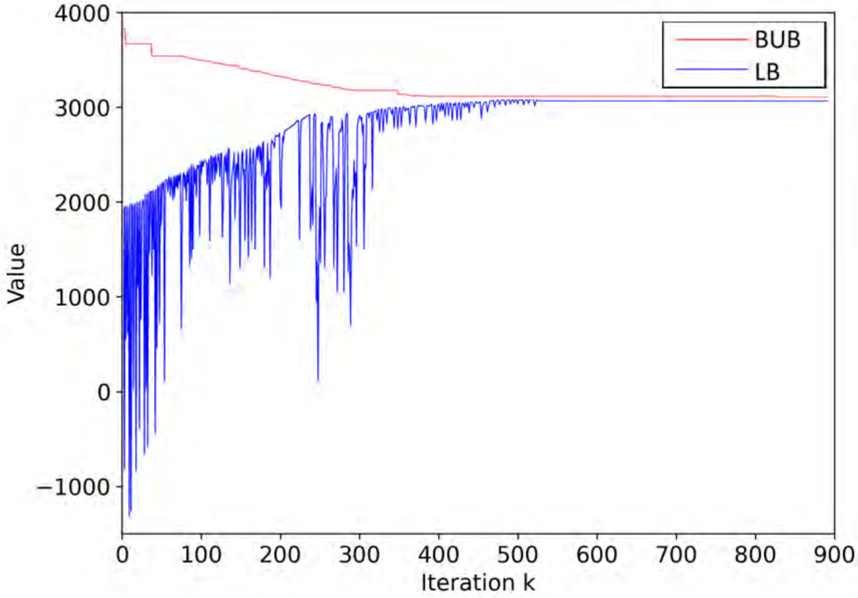


Figure 7: Convergence of the best upper bound and lower bounds using the Lagrangian relaxation-based algorithm

Technical Transfer and Commercialization

Presentations & Publications

The research described in this report was presented at the first FERSC annual meeting, held at Texas A&M University on April 25-26, 2024. The quantitative part of the research was further presented in the Inaugural Future of Transportation Summit, held at the US Department of Transportation headquarters in Washington DC, on August 13-15, 2024. We plan to prepare two journal articles based on the research described in the report.

Community Engagement

While conducting the surveys, we have reached out to the public sector, drayage operators, and labor and trade organizations to describe this research and what we expect from the project. We will make the report available upon request by the contacted stakeholders and other members interested in vehicle automation in the truck drayage community.

Other relevant efforts

Nothing to report.

Summary and conclusions

The integration of vehicle autonomation is poised to significantly impact the operational efficiency and cost-effectiveness of drayage operations. Focusing on terminal-to-terminal drayage operations, we investigate the prospect of vehicle automation from both qualitative and quantitative aspects. On the quantitative side, we formulate an integer linear programming model in a time-expanded network, which seeks to minimize the system total cost while considering the flow of trucks and containers. While having an autonomous truck will incur additional capital cost (measured as depreciation cost on a daily basis), an autonomous truck does not require a driver board nor operation break, thereby enhancing the efficiency of drayage operations.

By numerically implementing our optimization model in the terminal-to-terminal drayage operation context in the Chicago metropolitan region, we find that as the penetration of autonomous trucks increases in a fixed-size fleet, the system total cost will continuously decrease. This is largely due to the longer working hours of autonomous trucks without taking a break as required by conventional trucks with human drivers. Moreover, if a drayage operator could freely determine its fleet size, the optimal fleet size for autonomous trucks would be much larger than the optimal size of conventional trucks. Although having a larger fleet size increases truck operating cost and depreciation cost, a larger fleet of autonomous trucks also allows for timelier pickup and delivery of containers, which reduces time penalty cost and leads to reduced system total cost.

Apart from the potential benefits, the deployment of vehicle automation, more specifically ADS, in drayage operation is also faced with challenges and uncertainties. The findings from the qualitative part of our study suggest that while interviewees recognized the advantages of conducting small-scale pilot test of ADS trucks in middle-mile, especially in privately owned properties, if ADS is to be widely adopted for middle-mile freight, it must demonstrate significant capabilities. It will need to be able to replicate the driving abilities of a professional trucker, matching or exceeding the current safety performance by humans. Since ADS is expensive to develop and build, the only way it can lower costs overall is by replacing human labor. Any pathway to extensive use of ADS on public roads will therefore involve:

- The technology demonstrating a high safety standard;
- The technology replacing human labor;
- Technology that understands and addresses the real world needs/problems of the trucking industry (such as weather, grade, etc.);
- Public acceptance of ADS; and
- A regulatory environment ensuring ADS can legally operate without human "safety drivers", and with clear guidelines for development.

This is complicated by the resistance of labor unions to the replacement of human jobs, and by the specter of the "first big crash" – even a well-tested ADS will eventually be involved in a crash that results in the loss of life or large sums of money, and interviewees felt that this would set back public acceptance and technological development. The "self-fulfilling prophecy" of ADS needing to generate performance and safety data for insurance companies, fleet operators, regulators, and the public, but lacking the ability to do so without support from those same groups, will delay deployment. This can be counteracted by a thorough process of testing, incremental deployment, campaigns for public acceptance of ADS on the roads, and the avoidance of overpromising. This is where governments and universities may be able to play a central role by providing objective and transparent testing of ADS technologies.

Regulatory bodies can speed the safe development and deployment of ADS with clear rulemaking and standards made in consultation with stakeholders including ADS developers, trucking operators, and the public. The long-term financial viability of ADS development relies on the technology becoming attractive to fleet operators, its target market. ADS must prove it can perform to operator standards.

Finally, fully autonomous driving is not the only prospect for enhancing the efficiency in the middle mile, or in trucking more generally. Other technological innovations such as platooning, container consolidation, data coordination between fleet operators and distribution centers, along with limited driving automation, are already seeing implementation without sharing the potential drawbacks of fully autonomous vehicles. It is possible that the full benefit, cost, and safety promises of ADS will only manifest in the long term. Stakeholders should remain open to this and other possibilities and require the technology to prove itself useful before fully harnessing the power of vehicle automation in drayage operations.

Appendices

Appendix A: Interview questions

University of Illinois at Chicago

Project Title: **Understanding and Modeling Middle-Mile Logistics Automation**

Document: **Interview questions.**

The interviews will use a semi-structured format, and thus the following questions will be used to guide the discussion.

The following informed consent confirmation will be read to the participants before the initial meeting, individual interview, and focus group session. Respondents who do not verbally consent/agree will not be asked the interview questions. Potential subjects will be all English-speaking.

You understand that your participation in this study is entirely voluntary and that you can withdraw from the study at any time without penalty. The research team will exclude your name from any reports and will maintain your privacy whether you choose to participate in the study or not.

You understand that your participation in this study will not pose any physical risks to you personally and that you can skip any questions you are not comfortable answering.

You understand that you will not directly benefit from participating in the study, but that the study may be of benefit to governments, organizations, and individuals interested in utilizing the findings from this study to their services or advocacy.

If you have any questions about this study, feel free to ask them now or anytime throughout the study by contacting:

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If you have any questions about your rights as a research subject, you may write or call OPRS at the following address:

Office for the Protection of Research Subjects (OPRS)
1737, W. Polk Street, M/C 672
203 Administrative Office Building
Chicago, Illinois – 60612.
Phone: (312) 996 1711 or toll free: 866-789-6215
Email: uicirb@uic.edu

Agreement to Participate in Research:

By agreeing to participate in the study and you are giving Professor Kawamura and his associates permission to present this work in written and oral form, without further permission from you.

If you agree, please say "I agree".

If you do not agree, please say "I do not agree".

Questions for Automated Driving Systems Developers:

1. The driver shortage has been a concern in trucking for a long time. What are the possibilities and limits of automation in addressing this problem?

2. Is the middle mile easier to automate than other parts of the chain? Why or why not?

3. Will the costs of automation and newer info tech – training, energy, software, contracting, switching from older systems – be sustainable for smaller logistics companies? How do you see automation affecting the market shares of small and large companies?

4. How might automation change the labor force - what positions will be created when firms switch to ADS, and in what number? How easy it is to train someone to switch to maintaining ADS, or from driving to remote operating?

5. What is the state of regulation in automation (FMCSA, NHTSA, state, city)? How do you see that changing? How should regulators approach this technology?

6. If automation delivers on its promises for driving the middle mile, what might the chain of the future look like? What problems can automation, as we know it, solve? What might it be unable to solve?

7. Chicago has a large number of intermodal rail yards, with drayage moving goods between them. What are the characteristics of a route that's easy for ADS to drive? Will it be possible to route yard-to-yard drayage through Chicago, or will it need to take longer detours?

8. Are self-driving trucks ready for deployment in cities? What are the challenges? What would be the best scale for an ADS pilot program in a city like Chicago? What would success look like?

9. ADS perform much better when the infrastructure is built to accommodate them – things like smart parking spaces, road signs, traffic monitors embedded in the roads themselves. What is standing in the way of building this into our infrastructure? What V2I infrastructure could be built the fastest? What might V2I regulation look like? How can we handle the security concerns associated with V2I?

10. There is a lot of potential for information sharing between ADS on the roads. Can your vehicles communicate with vehicles made by other ADS companies?

Questions for Operators of Distribution Centers, Drayage, and Middle-Mile Logistics:

1. How is the middle-mile freight volume and also shipments split between small and large companies currently?

2. Chicago has a large number of intermodal rail yards, with drayage moving goods between them. What are drayage issues specific to Chicago? How could we improve those?

3. The driver shortage has been a concern in trucking for a long time. What are the possibilities and limits of automation in addressing this problem?

4. Is the middle mile easier to automate than other parts of the chain? (Answer appears to be yes – short, well-mapped routes between fixed DCs/retail)

5. Will the costs of automation and newer info tech – training, energy, software, contracting, switching from older systems – be sustainable for smaller logistics companies? How do you see automation affecting the market shares of small and large companies?

6. How might automation change the labor force - what positions will be created when firms switch to ADS, and in what number?

7. What is the state of regulation in automation (FMCSA, NHTSA, state, city)? How do you see that changing? How should regulators approach this technology?

8. If automation delivers on its promises for driving the middle mile, what might the chain of the future look like? What problems can automation, as we know it, solve? What might it be unable to solve?

9. What are the major challenges facing drayage operations in the Chicago region?

10. Where is (are) the main bottleneck(s) in the Chicago region?

11. For drayage operations in Chicagoland, is it more about container movement between different railroads, or more about draying containers/trailers to local distribution centers? What is the rough share of containers/trailers of these two types in the region?

12. What are the rough percentages of intermodal freight arriving in Chicago intermodal years carried by 40-/48-ftcontainers and by trailers? Does the size difference require different drayage equipment types?

13. How do drayage operators operate trailers/chasses, containers, and tractors? In the Chicago region, are they mainly large operators, or there are many smaller operators? Are there rules/standards for empty trailer/chassis repositioning?

14. To what extent has automation been applied to intermodal yards for drayage truck pick-up and delivery?

15. Is there a first-order cost estimate of automated vs. human-driven trucks for drayage operations?

16. Whether/how do drayage operators cooperate with each other and share resources (containers, chassis/trailers, tractors/drivers)? Do you think the existing cooperation/resource-sharing mechanisms will change after automation is introduced? How?

Questions for Governmental Policymakers and Regulators:

1. We have seen massive supply chain disruptions during and after the pandemic – what can be done to make the chain resilient?

2. (Depending on the interviewee) There are labor concerns about automation. How might labor concerns shape the rollout of Automated Drayage System?

3. What is the state of regulation in automation (FMCSA, NHTSA, state, city)? How do you see that changing? How should regulators approach this technology?

4. Are self-driving trucks ready for deployment in cities? What are the challenges? What would be the best scale for an ADS pilot program in the Chicago region? What would success look like?

5. Automated Driving Systems perform much better when the infrastructure is built to communicate with them – things like smart parking spaces, road signs, traffic monitors embedded in the roads themselves. What is standing in the way of building this into our infrastructure? What Vehicle to Infrastructure (V2I) could be built the fastest? What might V2I regulation look like? How can we handle the security concerns associated with V2I?

6. Are you worried about the cybersecurity implications of ADS?

Questions for Lobar and Trade Organizations:

1. The driver shortage has been a concern in trucking for a long time. What are the possibilities and limits of automation in addressing this problem?

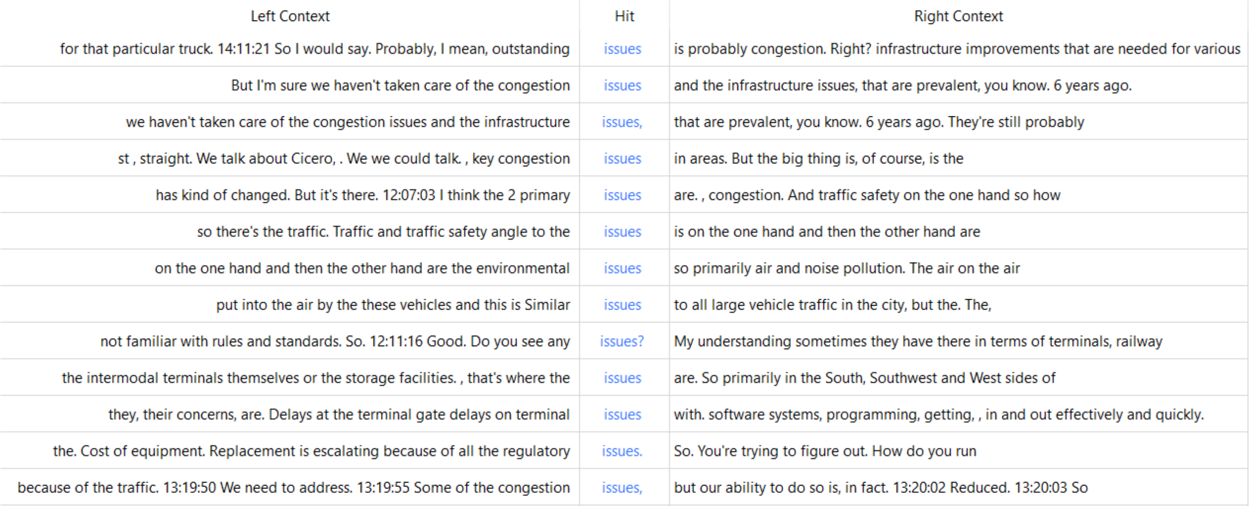
2. How might automation change the labor force - what positions will be created when firms switch to ADS, and in what number? How easy it is to train someone to switch to maintaining ADS, or from driving to remote operating?

3. Chicago has a large number of intermodal rail yards, with drayage moving goods between them. What are drayage issues specific to Chicago? How could we improve those?

4. What should the retraining/workforce development process look like for a just transition to automation?

Appendix B: Concordance analysis

Topic: Current Issues
Target word: "issues" or "issues"



Left Context	Hit	Right Context
for that particular truck. 14:11:21 So I would say. Probably, I mean, outstanding	issues	is probably congestion. Right? infrastructure improvements that are needed for various
But I'm sure we haven't taken care of the congestion	issues	and the infrastructure issues, that are prevalent, you know. 6 years ago.
we haven't taken care of the congestion issues and the infrastructure	issues,	that are prevalent, you know. 6 years ago. They're still probably
st , straight. We talk about Cicero, . We we could talk. , key congestion	issues	in areas. But the big thing is, of course, is the
has kind of changed. But it's there. 12:07:03 I think the 2 primary	issues	are. , congestion. And traffic safety on the one hand so how
so there's the traffic. Traffic and traffic safety angle to the	issues	is on the one hand and then the other hand are
on the one hand and then the other hand are the environmental	issues	so primarily air and noise pollution. The air on the air
put into the air by the these vehicles and this is Similar	issues	to all large vehicle traffic in the city, but the. The,
not familiar with rules and standards. So. 12:11:16 Good. Do you see any	issues?	My understanding sometimes they have there in terms of terminals, railway
the intermodal terminals themselves or the storage facilities. , that's where the	issues	are. So primarily in the South, Southwest and West sides of
they, their concerns, are. Delays at the terminal gate delays on terminal	issues	with. software systems, programming, getting, , in and out effectively and quickly.
the. Cost of equipment. Replacement is escalating because of all the regulatory	issues.	So. You're trying to figure out. How do you you run
because of the traffic. 13:19:50 We need to address. 13:19:55 Some of the congestion	issues,	but our ability to do so is, in fact. 13:20:02 Reduced. 13:20:03 So

Topic: Drayage automation
Target word: amazon

Left Context	Hit	Right Context
e companies more interested in automation being the cargo owners themselves. An	Amazon,	a Walmart, a target. Wanting to invest. Either in their own
try to move, to. 0 carbon fuels. It's pressure from the customer.	Amazon.	These are the people and others like them that are moving
am talking about. Generally speaking, class 7, 8 trucks. I'm not talking about	Amazon	delivery vans. Etc. But again. You can't have a driverless
Amazon delivery vans. Etc. But again. You can't have a driverless	Amazon	delivery, Van, unless you're willing to go out to the

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