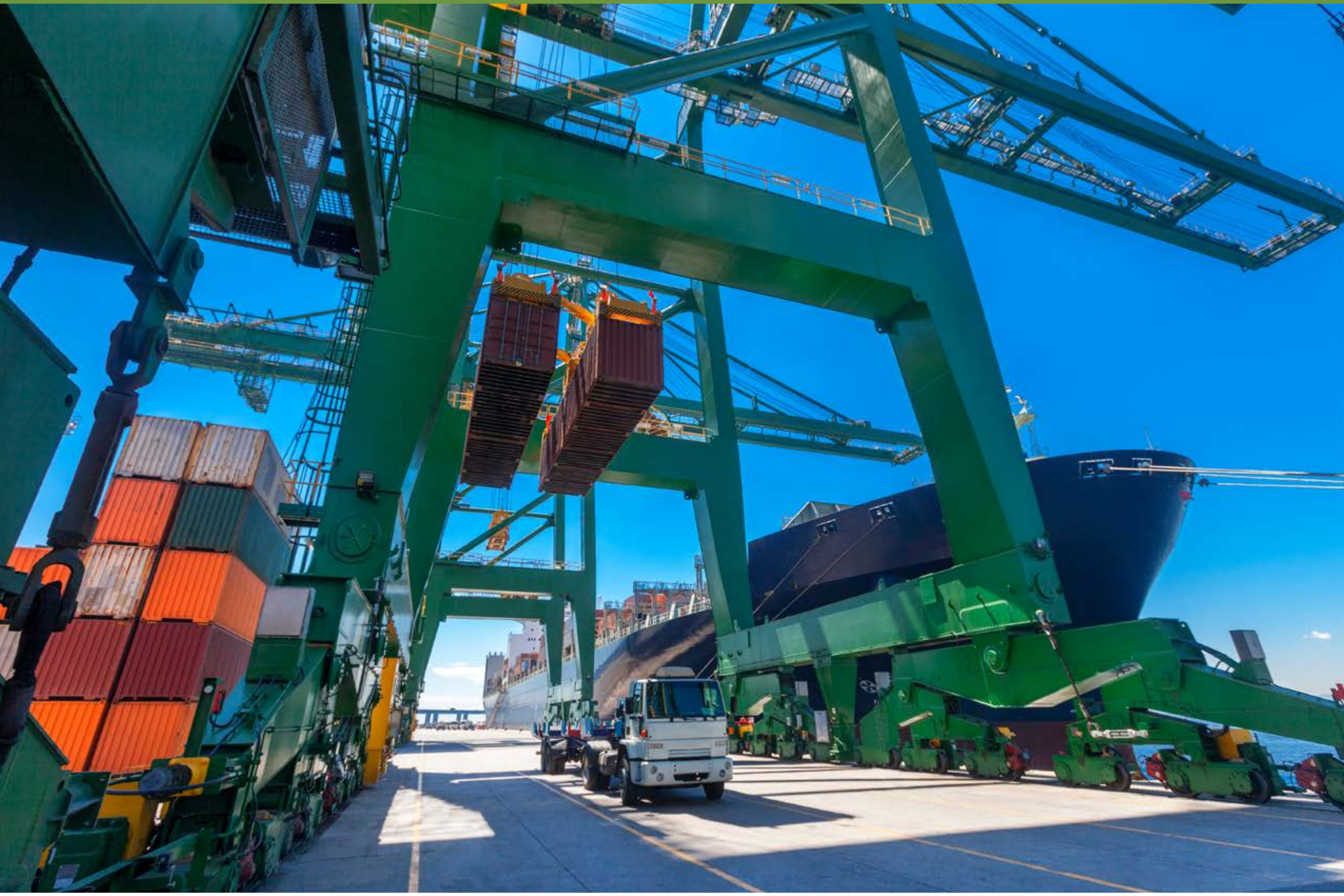

TOWARD GREENER SUPPLY CHAINS

A CRITICAL ASSESSMENT OF A MULTIMODAL, MULTINATIONAL FREIGHT SUPPLY CHAIN OF A FORTUNE 50 RETAILER

CRISTIANO FAÇANHA, ULISES HERNANDEZ, XIAOLI MAO, AND LETICIA PINEDA

icct
THE INTERNATIONAL COUNCIL ON CLEAN TRANSPORTATION

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LIST OF ACRONYMS

3PL Third-party logistics provider
CFS Consolidated freight station
CO_2 Carbon dioxide
DPF Diesel particulate filter
ECA Emission control area
EPA United States Environmental Protection Agency
FCL Full container load
GDP Gross domestic product
GHG Greenhouse gas
GLEC Global Logistics Emissions Council
GVWR Gross vehicle weight rating
HDV Heavy-duty vehicles
ICE Internal combustion engine
IMO International Maritime Organization
km Kilometer
LCL Less than container load
LNG Liquefied natural gas
NO_x Nitrogen oxides
O-D Origin-destination
$PM_{2.5}$ Particulate matter with a diameter of 2.5 micrometers or less
PO Purchase order
RDC Rapid deployment center
SAVE Systematic Assessment of Vessel Emissions
SCR Selective catalytic reduction
SDC Stocking distribution center
SKU Stock keeping unit
SO_x Sulfur oxides
TEU Twenty foot-equivalent unit
THD The Home Depot Inc.
TSLD Transload facility
ZEV Zero-emission vehicle

EXECUTIVE SUMMARY

Global trade has increased significantly in recent decades, and some forecasters expect goods movement activity to triple or quadruple within the next few decades. All modes of freight transportation rely almost entirely on fossil fuels, and carbon emissions from marine transport have grown even faster than overall activity, principally due to inefficiencies in goods movement and lagging technology adoption. This study evaluates the capacity of current and future technologies and strategies to improve the energy and environmental performance of a real-world global supply chain. It also highlights the drivers of and barriers to a greener freight sector, and explores how to foster collaboration across industry, government, and civil society to facilitate future implementation of technologies and strategies.

Utilizing data from The Home Depot Inc. (THD), the third-largest U.S. importer of containerized cargo and a leader in the U.S. Environmental Protection Agency's SmartWay program, this study evaluates a supply chain from China to the continental United States through the port of Shenzhen and the ports of Los Angeles and Long Beach. The supply chain is divided into six segments, shown in Figure ES1. The six segments have different relative contributions to supply chain impacts because they have different intensities of energy consumption and emissions. For example, while marine represents more than 90% of the freight activity along this supply chain, it accounts for just over half of CO_2 emissions. That is because moving freight by vessels is significantly more efficient than other modes. But while large, oceangoing vessels are more energy-efficient than trucks, due to larger cargo capacity, they are also less effective at reducing local pollutants because of the high sulfur content of marine residual fuels. Large ships also have less stringent vessel emission controls relative to diesel fuel and truck emission control equipment.

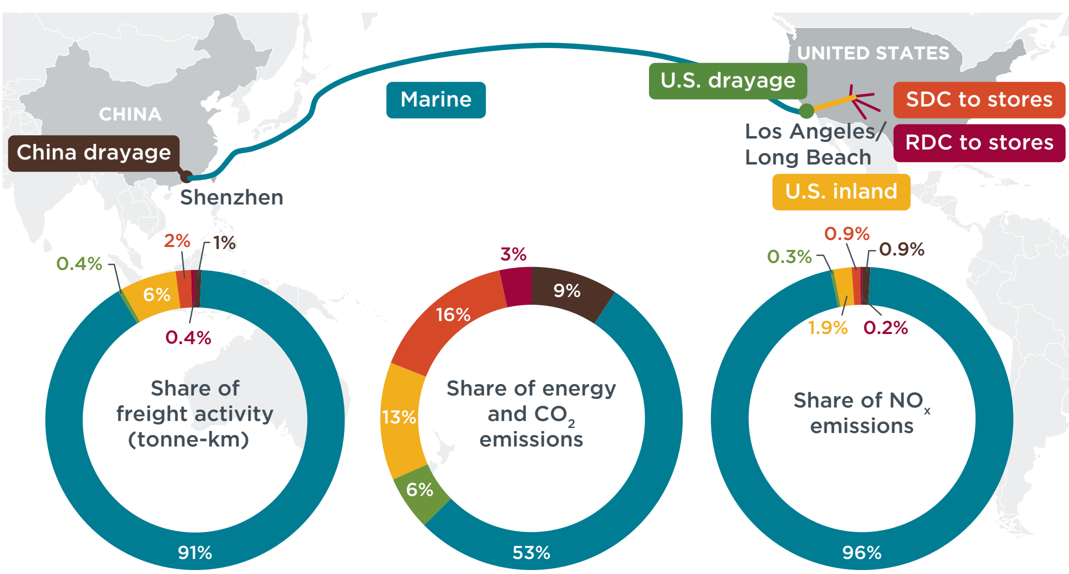


Figure ES1. Supply chain characterization

This study evaluates the impact of technologies and strategies on reducing energy consumption and emissions under three modeled scenarios. The *Conventional* scenario is a reference supply chain that does not contain improvements already incorporated by THD. The *Green* scenario is the current THD supply chain with implemented technologies and strategies (the data from THD is at times supplemented by current industry best practices). Finally, the *Green Plus* scenario models a hypothetical future supply chain with potential technologies and strategies.

Three types of strategies are applied, to varying degrees, in the *Green* and *Green Plus* scenarios: (1) Logistics strategies optimize freight activity by increasing vehicle/vessel utilization, reducing empty kilometers, and optimizing routes; (2) Modal strategies promote the shift of freight activity to cleaner and more efficient modes; and (3) equipment strategies reduce the energy consumption and emissions intensity of transportation equipment and fuels.

RESULTS HIGHLIGHTS

The findings of this study help build the case for adopting strategies similar to those taken by industry leaders. In the *Green* scenario, significant reductions—27% for energy use and CO_2 emissions, and 23%–25% in the case of local pollutants—are achieved by adopting currently available technologies and strategies (see Figure ES2). For land-based segments, reductions of local pollutants of 41%–63% can currently be achieved, primarily by prioritizing the cleanest truck carriers in use. For the marine segment, more moderate reductions in local pollutants of 23%–24% can be achieved today, primarily through cutting consumption of dirty marine fuel.

Regarding energy consumption and CO_2 emissions, savings for the land-based segments in the *Green* scenario are roughly equivalent between logistics and equipment strategies, with relatively smaller savings from modal strategies. THD relies on a combination of measures to improve logistics efficiency, including load consolidation in distribution centers, cube optimization to maximize truck and container utilization, and the use of higher-capacity equipment. In addition, THD prioritizes the use of the most efficient truck carriers registered in the North American SmartWay program. In the marine sector, THD relies more heavily on equipment strategies and, to a lesser extent, modal strategies such as deploying larger vessels.

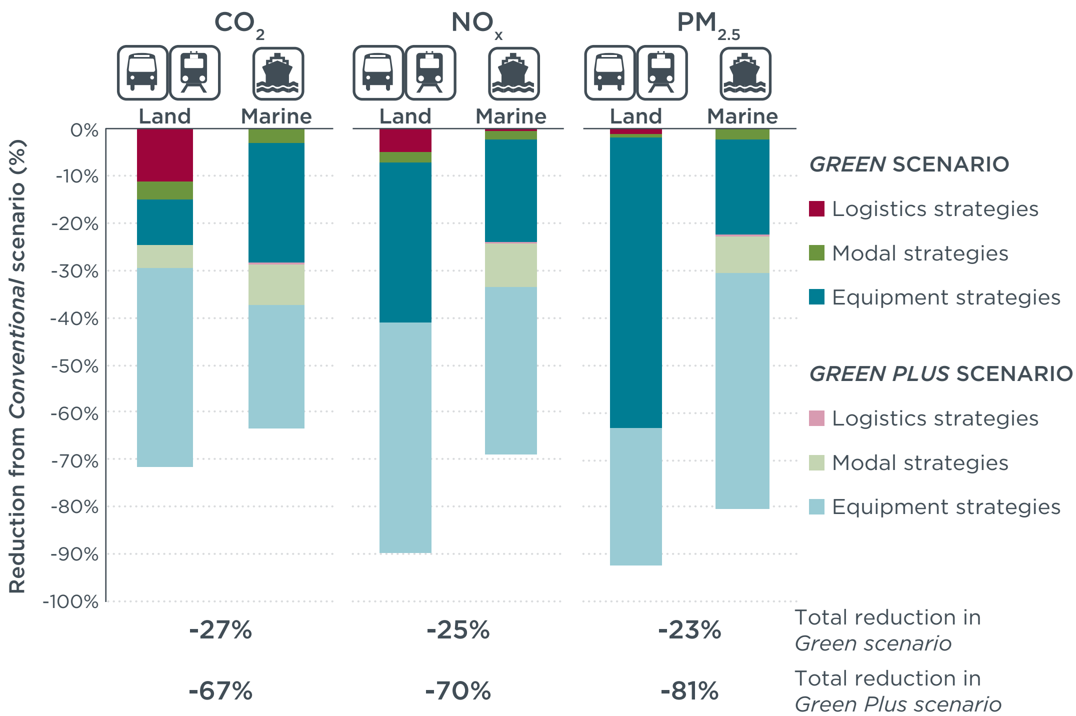


Figure ES2. Summary of supply chain energy and emissions reduction potential.
Note: Land-based segments calculated $PM_{2.5}$ emissions and the marine segment calculated PM_{10} emissions. Approximately 96% of PM_{10} emissions are primary tailpipe emissions of $PM_{2.5}$.

This study also highlights the potential to further improve the supply chain of THD. In the *Green Plus* scenario, overall future energy use and CO_2 emissions can be reduced by 67% from the *Conventional* scenario, and more than twice the savings in the *Green* scenario (Figure ES2). Local pollutants can be reduced by 70%–81% from the *Conventional* scenario, depending on the pollutant, primarily by more effective emission control technologies in trucks, ships, and locomotives.

The most certain path to reducing land-based local pollutants further is to improve truck and rail technologies. While these technologies can reduce energy consumption and CO_2 emissions by more than 50% from the *Conventional* scenario, they can reduce local pollutants by almost 80% for nitrogen oxides (NO_x) and 90% for particulate matter with a diameter of 2.5 micrometers or less ($PM_{2.5}$). The potential for reduction is even higher if more aggressive assumptions for equipment electrification are considered, but this analysis limits electrification to short- and medium-distance shipments). The same applies to the marine segment, where introducing low- and zero-carbon fuels could achieve large reductions under the *Green Plus* scenario.

ECONOMIC AND POLICY IMPLICATIONS

All strategies with an impact on energy use and CO_2 emissions reduce fuel consumption, and this results in direct fuel-related cost savings. In the United States, fuel represents, on average, 22% of trucking costs. Greener modal strategies will shift freight away from trucking, and thus it is assumed that overall costs will decrease, because rates for other modes are typically cheaper on a tonne-kilometer basis.[1] Improved logistics strategies will also reduce the costs associated with distance traveled.

Although the reduction of local pollutants such as NO_x or $PM_{2.5}$ does not deliver direct cost savings to shippers and carriers, this has critical social and health benefits. Cost-benefit analyses of Euro VI-equivalent standards for heavy-duty trucks indicate that the economic benefits from lower premature mortality outweigh technology costs by a ratio of 8–16 to 1. Compared with land-based control measures, those applied on ships have been shown to be even more cost-effective.

It is important to understand the drivers of each of the three strategy types—logistics, modal, and equipment—and the barriers to adoption that exist. Logistics strategies are primarily driven by industry. Perhaps the most important barrier to better logistics efficiency is limits on empty mileage reduction. This is often because of trade flow imbalance, lack of visibility of truck capacity, and lack of collaboration between shippers and carriers. Other important barriers are freight capacity limitations and congestion in ports and other major freight facilities. Bilateral partnerships and information-sharing platforms for load matching could increase collaboration among industry partners and help fill transportation equipment.

Modal strategies are driven by infrastructure availability and investment, market deregulation, freight pricing, and the relative competitiveness of different modes in different markets and regions. Important barriers prevent more mode shifting away from trucking. These include more demand for smaller and just-in-time shipments, limited public funds for rail and waterway infrastructure, improved energy efficiency of trucks, slower innovation in rail and waterway transportation compared with trucking, and rail and port air and noise pollution. Government can help overcome these barriers through infrastructure investments and harmonization, rail deregulation, freight user fees, and greenhouse gas (GHG) pricing mechanisms. The rail and waterway sectors can also enhance competitiveness by improving asset and staff productivity, investing in data solutions to reduce costs and provide customers with a more seamless experience, and improving schedules to provide more reliability and attract new traffic.

Many barriers prevent faster efficiency improvements in transportation equipment. Trucking, for example, is a highly disaggregated sector where most carriers are very small and operate on razor-thin margins. This makes it difficult to invest in more-efficient trucks without financial assistance. Drayage trucks, locomotives, and marine vessels also linger in fleets for decades, thus delaying the benefits of new technologies.

There are many opportunities, however, to overcome these and other barriers. In addition to GHG and fuel efficiency regulations for heavy-duty trucks, governments can provide additional incentives for equipment retrofits, accelerated replacement, and fleet electrification. Fuel quality standards and low-carbon fuel mandates could also lead to better sustainability of diesel and marine bunker fuel. Governments can also implement voluntary green freight programs that provide incentives for shippers to hire the most efficient carrier fleets, and for carriers to use real-world efficiency data to improve truck and driver performance.

Future supply chains can become substantially cleaner, more efficient, and more cost-effective by leveraging coordinated action by government and industry. Good data and reporting are crucial in these efforts.

1 This assumption typically does not apply to short-distance trips where rail is not cost-competitive with trucks.

CHAPTER 1. **INTRODUCTION**

Bolstered by a variety of factors, including globalization, a decrease in transportation costs, ubiquitous information technologies, and strong economic growth in emerging markets, global trade has increased significantly over recent decades. Between 2000 and 2016, global freight tonnage grew from 7.3 billion to 12 billion tonnes per year, a 3.1% average annual growth, and its value increased from $1.4 trillion to $4.4 trillion, or an average increase of 7.4% per year (United Nations Conference on Trade and Development [UNCTAD], 2018).[2] For every 1% increase in global gross domestic product (GDP), there is a corresponding 1.2%–1.4% increase in global freight (International Transport Forum [ITF], 2017).

Global trade has important economic benefits in terms of job creation and enabling different regions to specialize in products where they have a competitive advantage. Additionally, when there is a wide array of high-quality products available at lower prices, consumer welfare is enhanced. Nonetheless, when this is achieved by moving freight over long distances and at faster speeds, it has negative impacts that include adverse effects on climate and public health.

All modes of freight transportation rely almost entirely on fossil fuels, which are the primary cause of greenhouse gas (GHG) emissions and global warming. As observed in Figure 1, freight-related CO_2 emissions are projected to increase by 157% on the road and 77% in the marine mode by 2050. Reducing CO_2 emissions from the freight sector is thus of critical importance in seeking to meet global climate goals.

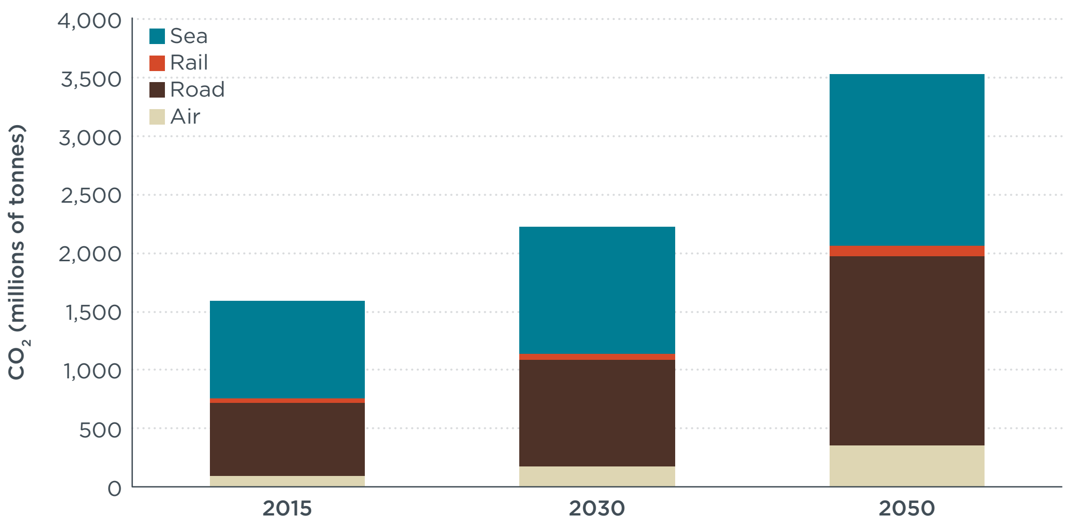


Figure 1. Growth in freight CO_2 emissions by mode (ITF, 2017). Projections for 2030 and 2050 assume a freight growth/GDP growth elasticity of 1.2.

2 All references to tonnes in this report refer to metric tons (1,000 kg) unless otherwise noted.

The impact of freight on near-term global warming is more acute because on-road diesel and the heavy bunker fuels used in marine shipping are among the primary sources of black carbon. This short-lived climate pollutant has a global warming potential that is 910–3,200 times that of CO_2 (Bond et al., 2013). Furthermore, when black carbon lands on ice or snow, it reduces reflectivity and favors more sunlight absorption, thus increasing heat and accelerating the melting of glaciers and ice caps. In this study, reductions of black carbon are captured indirectly through reductions in particulate matter with a diameter of 2.5 micrometers or less ($PM_{2.5}$), as black carbon is a fraction of $PM_{2.5}$.

Road freight activity also places a significant burden on human health. Heavy-duty diesel trucks are high emitters of $PM_{2.5}$ and nitrogen oxides (NO_x), both of which are linked to a range of adverse health outcomes. These include ischemic heart disease, chronic obstructive pulmonary disease, lung cancer, and ultimately years of life lost to disease and premature death (Chambliss, Miller, Façanha, Minjares, & Blumberg, 2013). Freight imposes a higher health burden on populations exposed to ports, highway corridors, railyards, and distribution centers. It is common for poor communities to be close to these centers of activity, and they are affected disproportionally by freight activity (Matsuoka, Hricko, Gottlieb, & De Lara, 2011). Therefore, making freight cleaner and more efficient is a priority for addressing social and environmental justice concerns.

Improving freight efficiency and environmental performance is an effective strategy for emissions control. On-road heavy-duty vehicles (HDVs), for example, represent 11% of the global vehicle fleet but consume 46% of on-road fuel and emit 71% of on-road particulates that negatively affect human health (Kodjak, 2015). Although these figures include buses, freight trucks still account for the majority of fuel consumption and particulate emissions. Government agencies have implemented a variety of policies to improve truck efficiency and environmental performance, including regulations, market-based approaches, and fiscal instruments.

The key vehicle markets of the United States, Canada, China, and Japan have regulated the efficiency of new HDVs, and all major vehicle markets have adopted Euro VI-equivalent emission standards for new HDVs—the cleanest to date. In addition to enhancing the environmental performance of new vehicles, efforts are needed to improve in-use fleet performance. Some countries have developed voluntary green freight programs; these are market-based mechanisms that provide information and promote fuel-saving technologies and strategies while rewarding the best carriers and shippers. One example is the U.S. Environmental Protection Agency (EPA)'s SmartWay program, launched in 2004. The EPA subsequently, in 2012, joined forces with Natural Resources Canada to expand the program in Canada. This created a single North American SmartWay program. Programs in other regions—in China, for example, there is the China Green Freight Initiative—are in different stages of implementation (Baker et al., 2015).

Keeping in step with on-road emission controls, the international community is working to reduce ship emissions. Sofiev et al. (2018) estimate that shipping-related $PM_{2.5}$ concentrations will cause more than 100,000 deaths annually at current marine fuel quality levels. Policies under development include more-stringent marine engine standards, low-emission zones around ports and coastlines, and financial incentives to support short-term emission control technologies and long-term decarbonization approaches.

In parallel with government action, leading companies have begun addressing environmental challenges as part of corporate social responsibility efforts and international commitments. These organizations also seek the cost savings generated by more-efficient freight operations. This is a triple-bottom-line approach whereby companies set targets not only for financial gains, but also for social and environmental benefits (Elkington, 2004).

Government policies and industry-led actions are both necessary to address the climate and health effects from goods movement. However, information about the implementation of and effects of industry strategies is either lacking because of the competitive nature of industry data, or highly biased because of the lack of analyses by neutral parties. Analyzing successful cases of leading companies and showcasing relevant strategies can promote financial, environmental, and societal goals.

This study aims to develop an unbiased and technical evaluation of the supply chain emissions reduction strategies adopted by The Home Depot Inc. (THD), a top global company that represents a sizable share of global freight. The study also explores how industry-led activities and government policies can complement each other to achieve global climate and health goals.

CHAPTER 2. **SCOPE OF ANALYSIS**

This study evaluates a real-world global supply chain and calculates the emissions and energy savings from technology and strategies. First, the study estimates savings from strategies already implemented by THD, and this provides an industry benchmark. Second, the study assesses the potential for future strategies to further reduce energy consumption and emissions. Finally, the study highlights key stakeholders and opportunities for collaboration across industry, government, and civil society to facilitate implementing future strategies.

PARTNER SELECTION

THD was selected as the shipper partner because of its significant freight activity, its leadership in streamlining and reducing the environmental footprint of its supply chain under the SmartWay program, and its willingness to provide information and participate in the project.

THD is the largest home improvement retailer in the world, based on 2017 net sales. It sells an assortment of building materials, home improvement goods, lawn and garden products, and décor items. The company operates 2,284 stores in the United States, Canada, and Mexico and was the third-largest U.S. importer of containerized cargo in 2017 (Figure 2).

Actions to mitigate the company's environmental footprint extend to most of its operations. With respect to the transportation of goods, THD received the EPA's SmartWay Sustained Excellence Award five years in a row from 2013 through 2017. The award recognizes companies that take the lead in improving efficiency and contributing to cleaner air within their supply chains.

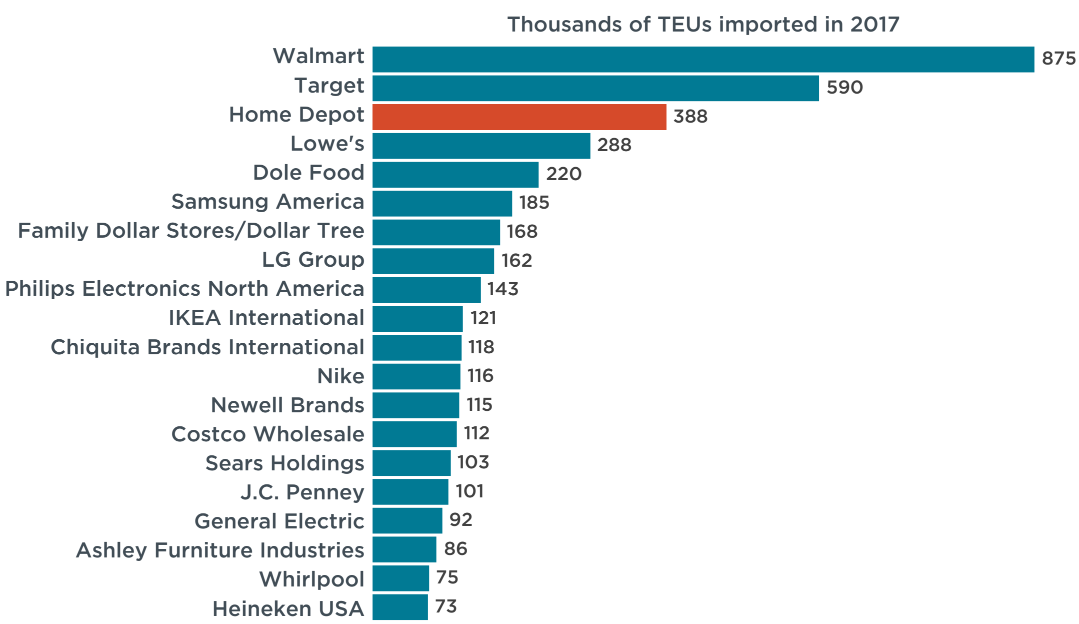


Figure 2. Largest U.S. importers of containerized cargo in 2017 (Johnson, 2018), based on number of twenty foot-equivalent units (TEUs)

SUPPLY CHAIN DEFINITION AND STUDY BOUNDARIES

This study evaluates a supply chain from China to the continental United States through the ports of Shenzhen in China and Los Angeles and Long Beach in California. As shown in Figure 3, the eastbound trade route from Asia to North America had by far the largest container traffic in 2017. This makes the study results relevant for a large share of the total global container market. Shenzhen ranks among the top three ports in terms of container traffic, with more than 25 million TEUs in 2017, and Los Angeles alone had the highest volume of container operations in the United States, with 9.3 million TEUs in 2017 (UNCTAD, 2018). A more detailed characterization of THD's supply chain is provided in Chapter 3.

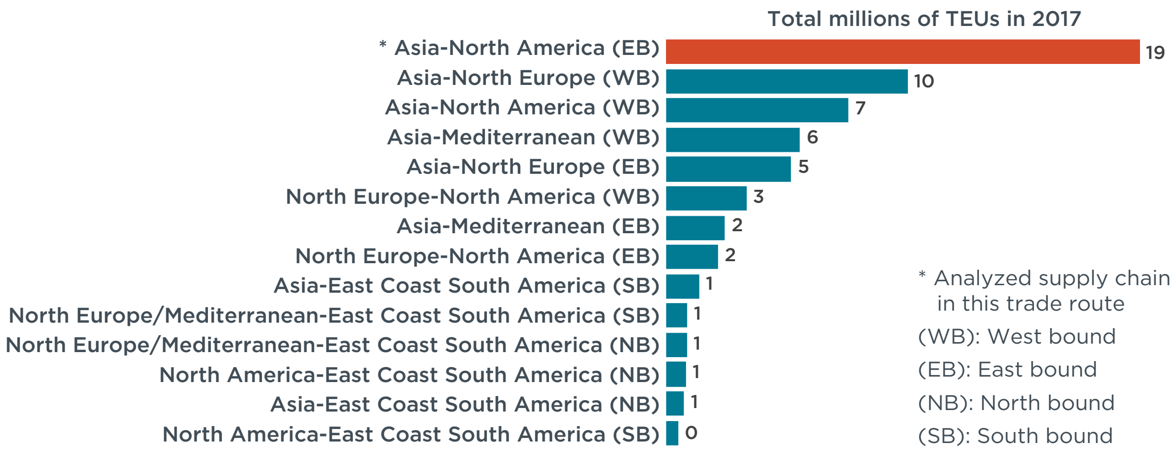


Figure 3. Largest trade corridors of containerized cargo in 2017. Adapted from World Shipping Council (2017)

The Asia-North America eastbound freight corridor, which is the busiest trade corridor in the world, accounts for the bulk of THD's U.S. imports, 86% of which come from China (Figure 4).

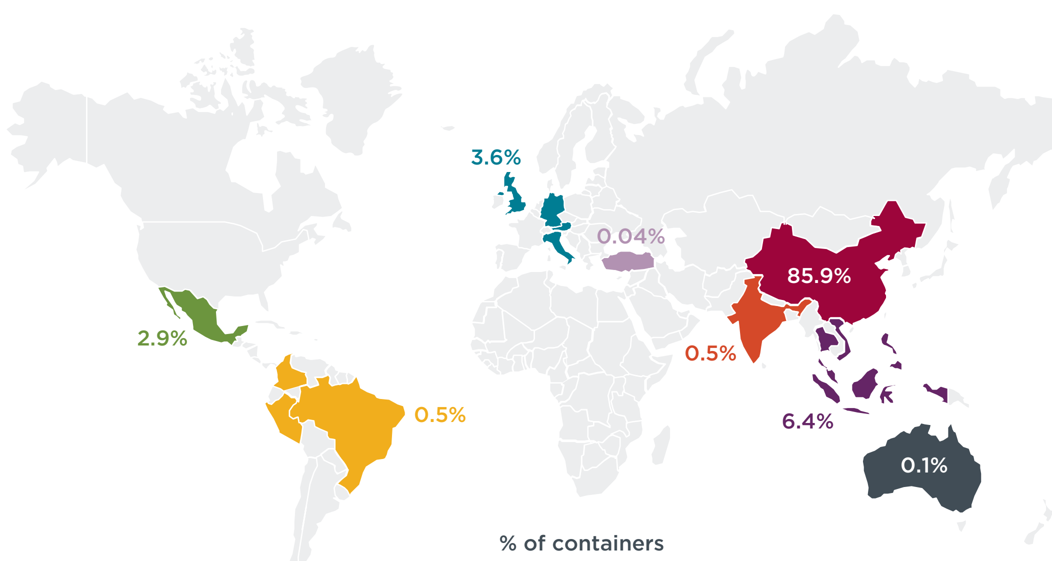


Figure 4. THD's imports by origin in 2017 (share of containers)

According to most definitions, a supply chain is a set of organizations directly involved in the upstream and downstream flow of products, services, finances, and/or information from a source to a customer (Mentzer et al., 2001). This broad definition covers most aspects of business operations—the sourcing of raw materials and inputs, goods manufacturing and assembly, storage, transportation, and product end of life such as recycling, reuse, and disposal—and all supporting business operations.

A full life-cycle analysis of THD's supply chain is not developed here. Based on the terminology of the Greenhouse Gas Protocol, the study includes downstream transportation and distribution within downstream scope 3 emissions (World Resources Institute & World Business Council for Sustainable Development, 2011), and it is limited to the transportation segments of the supply chain. These segments are the shipment of finished products from three Chinese suppliers through the ports of Shenzhen and Los Angeles and Long Beach, to distribution centers, and finally to stores in the United States. Energy and emissions associated with product manufacturing, storage, use, and end of life are beyond the scope of the study, as are energy and emissions associated with port terminals and distribution centers. The main rationale for limiting the project's scope to transportation energy and emissions is that transportation represents a sizable share of total supply chain emissions. In addition, energy and emissions are assessed on a tank-to-wheels basis, meaning that only those associated with fuel combustion are considered. Emissions from the fuel production and refining process, known as well-to-tank, are not considered, even though they can be significant.

SCENARIOS

This study evaluates the impact of technologies and strategies on energy consumption and emissions under three scenarios:

» ***Conventional* scenario.** Reference, or business-as-usual supply chain. It excludes the green strategies already incorporated by THD.

» ***Green* scenario.** Current THD supply chain with its already-implemented green strategies. The analysis relies on information and data obtained directly from THD where possible, and complements it with current industry best practices. The difference between the outputs from this scenario and those from the *Conventional* scenario are the savings from green strategies.

» ***Green Plus* scenario.** Future hypothetical supply chain with improvements to measures already implemented by THD. Potential technologies and strategies for future adoption are identified for each segment in the supply chain, and there are corresponding estimates of total energy consumption and emissions. Because of the different levels of maturity across equipment technologies, this scenario is further subdivided among short-term (2020), medium-term (2025), and long-term (2030). The difference in outputs between the *Green* and *Green Plus* scenarios reflects the potential savings from future improvements in the supply chain.

Although the scenarios include future projections of technology and strategy uptake, the study does not take into consideration any changes in shipment amounts. This is to more clearly isolate the effects of strategies on energy and emissions. However, freight volumes are increasing across all sectors and in all regions. Thus, to promote and sustain healthy environments and prosperity, it is crucial for governments and businesses to integrate greener technologies and strategies like those identified in this report.

CALCULATION METHODS

This study uses different methodologies to estimate land-based and marine supply chain energy consumption and emissions (see Appendix A). Land-based calculations are based on guidance from the Global Logistics Emissions Council (GLEC) Framework, although this study considers only tank-to-wheels energy and emissions, whereas the GLEC Framework includes a complete well-to-wheels methodology. Energy consumption and emissions are calculated as the product of freight tonnage, travel distance, and fuel efficiency/emissions factors. Freight tonnage and travel distances are based on disaggregated data from THD, while fuel efficiency/emissions factors are based on a combination of SmartWay data specific to THD operations and industry averages.

Marine calculations are based on the ICCT's Systematic Assessment of Vessel Emissions (SAVE) model. As with land-based calculations, disaggregated data on freight tonnage, travel distance, and specific vessel information was obtained from THD. This study uses the SAVE model to retrieve vessel-specific fuel efficiency/emissions profiles.

For both land-based and marine calculations, the *Green* scenario is modeled using actual data and the *Conventional* and *Green Plus* scenarios are based on information from THD and expert knowledge of future technology trends.

STUDY FEATURES

This is one of the first studies to link technology research, operational best practices, and emissions accounting methodologies in an in-depth assessment of a real-world supply chain (see the literature review in Appendix B). This contributes to research on freight sustainability by:

» **Using real-world data, rather than industry averages.** One of the most important limitations to developing accurate quantitative analyses of freight environmental performance is access to real-world data. By partnering with an industry leader, this study utilized disaggregated data on shipment weight and volume, origins and destinations, modes of transportation, equipment technology, and specific operational practices. This enables insights into which strategies are most effective under those conditions.

» **Assessing the impacts of already-adopted strategies.** The study models implemented strategies targeted at improving transportation efficiency and compares them with industry average values. In addition to providing a more accurate assessment of the impact of green strategies, this approach also supports their promotion. A description of the strategies evaluated in this study are included in Chapter 4.

» **Highlighting the magnitude of potential savings and increasing stakeholder awareness.** Because the study analyzes several strategies across the supply chain, it provides an opportunity to emphasize the magnitude of savings from each strategy. It also highlights the gap between industry leaders and standard practices, and serves as a benchmark for the industry.

» **Identifying priority areas for further improvement.** After developing a better understanding of THD's operations, the study identifies future strategies for further improvement of its supply chain. These findings inform priority areas for planning, research, collaboration with other stakeholders, and pilot projects.

- **Identifying the role of key stakeholders.** After a thorough evaluation of a complex supply chain, the study considers the roles of different stakeholders in the implementation of green strategies. This enables a qualitative assessment of policy implications for the different strategies and the role of multiple stakeholders in facilitating their implementation.
- **Demonstrating the feasibility of using detailed data while maintaining the confidentiality of strategic business information.** This is especially important given the increase of available data as more information technologies are implemented across different supply chain stages.

Study limitations are discussed in Chapter 7 together with an outline for future research.

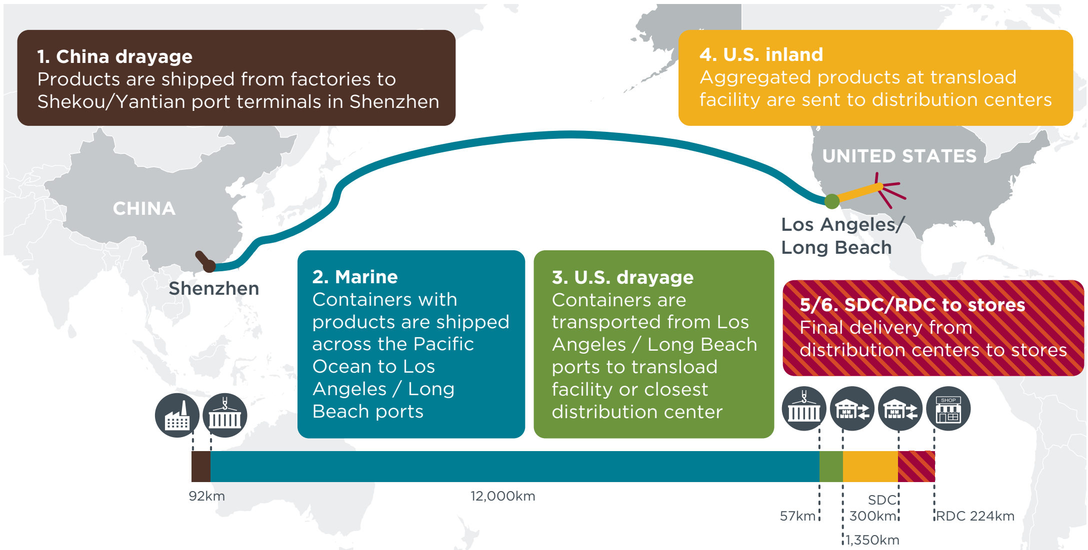
CHAPTER 3. **SUPPLY CHAIN CHARACTERIZATION**

THD imports products from about 615 factories in China to its nearly 2,000 stores in the United States. Given the large number of factories, stores, and products, this study is limited to three suppliers. These three were chosen to ensure a good mix of product characteristics and because of their willingness to share data (Table 1). The data considered in this study includes all shipments from these three suppliers to THD stores in the western United States in 2017. While total annual weight and volume shipped are roughly equivalent across the three suppliers, Supplier B has relatively fewer products and these have relatively larger weight and volume per unit. Supplier C, on the other hand, shipped more units of smaller products. Supplier A falls somewhere between Suppliers B and C.

Table 1. Main characteristics of selected suppliers

Supplier	Products	Total annual units	Total annual weight (tonnes)	Average weight (kg/unit)	Total annual volume (m^3)	Average volume (m^3/unit)
A	Ceiling fans	587,419	5,003	9	31,362	0.05
B	BBQ grills	109,430	4,453	41	30,545	0.28
C	Lighting fixtures and equipment	2,131,764	4,295	2	31,821	0.01

The supply chain is divided into six segments, each representing a transportation link between nodes where freight is transferred, consolidated, or stored (Figure 5). The following sections describe each of the segments.



Segment name	Origin nodes	Destination nodes	Transportation modes	Average Distance[a]
1. China drayage	13 factories in China: Supplier A: 1 factory Supplier B: 1 factory Supplier C: 11 factories	Two port terminals in Shenzhen metropolitan area (Shekou and Yantian)		92 km
2. Marine	Two port terminals in Shenzhen metropolitan area (Shekou and Yantian)	7 port terminals in Los Angeles/Long Beach		12,000 km
3. U.S. drayage	7 port terminals in Los Angeles/Long Beach	1 transload facility (TSLD) 1 stocking distribution center (SDC) in Mira Loma		57 km
4. U.S. inland	1 TSLD	4 SDCs 7 rapid deployment centers (RDC)		1,350 km
5. SDC to store	4 SDCs	615 stores		300 km
6. RDC to store	7 RDCs	622 stores		224 km

[a] Average distance adjusted by weight moved in each segment.

Figure 5. Detailed characterization of the supply chain

CHINA DRAYAGE

In 2017, the three suppliers combined shipped 13,750 tonnes in 1,778 containers from 13 factories located in the coastal province of Guangdong, China, to either the Shekou or Yantian container terminals, located about 40 km apart from each other (Figure 6).[3] All shipments in this segment were moved with drayage trucks, whose technology characterization is included in Chapter 4. Suppliers A and B each have one factory

3 This study uses containers as the main metric for marine freight activity, as opposed to the more commonly used TEU metric. For land-based segments the number of containers is a more accurate representation of the number of truck trips (1 container = 1 trip). Because more than 90% of the containers in the China drayage and U.S. drayage segments are 40-ft high cube, the number of TEUs can be easily calculated by multiplying total containers by two.

serving THD in this data sample, and the remaining 11 factories correspond to Supplier C. Although the farthest factory is 198 km from the port, the average weighted distance shipped from each factory is 92 km.

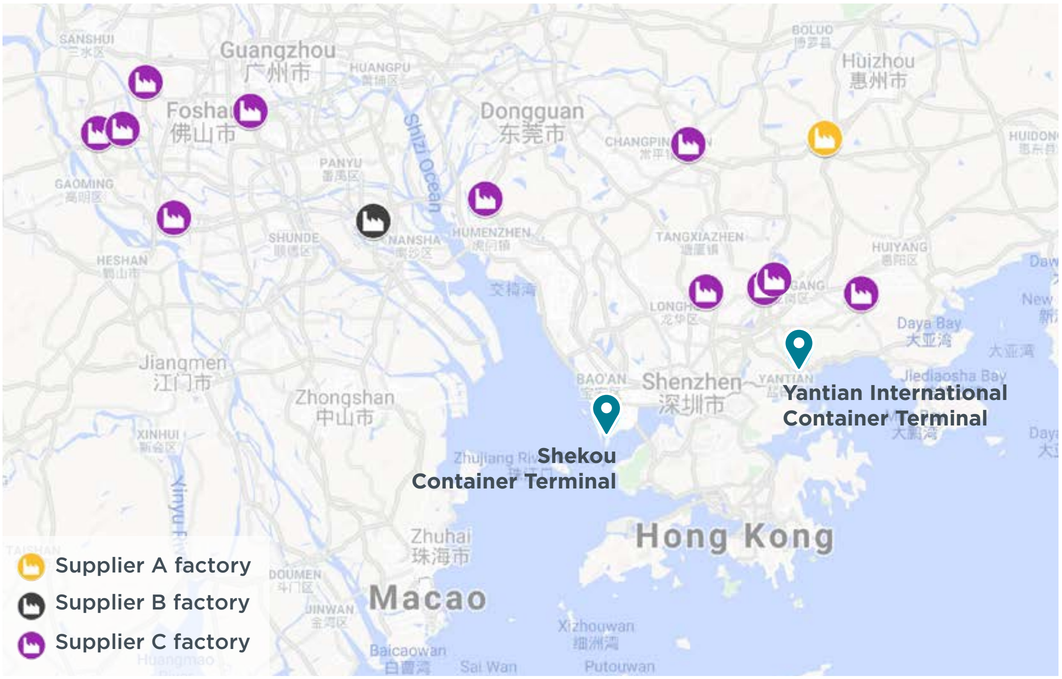


Figure 6. Location of Chinese supplier factories, port terminals and CFS facility. *Source*: Google Maps.

Because of large import quantities, THD optimizes purchase orders and ships most containers, 88%, directly from supplier factories to port terminals. For those containers with low utilization, THD operates a consolidated freight station (CFS) close to the Yantian terminal where these containers are filled with products from other THD suppliers.[4] Table 2 summarizes supplier data for direct shipments to ports and CFS shipments.

Table 2. Characteristics of China drayage shipments by supplier

Supplier	Type of shipment	Type of shipment (%)	Number of containers shipped	Container load average weight (tonnes)	Container average load factor
Supplier A	Direct to port	87.5%	443	10.9	89%
	CFS	12.5%	63	2.9	25%
Supplier B	Direct to port	100.0%	453	9.8	88%
	CFS	0.0%	—	—	—
Supplier C	Direct to port	77.9%	638	6.5	65%
	CFS	22.1%	181	1.0	13%

Figure 7 includes data by factory and illustrates how most shipments come from three factories, one serving each supplier. Together these three account for 85% and 73% of total weight and containers, respectively. The share by weight is higher than the share

4 Low factor utilization means considerable space available in the container, usually more than 50% of the total volume.

by containers for suppliers A and B, and the opposite is true for supplier C (recall from Table 1 that the products of suppliers A and B are heavier and larger than supplier C's products). As expected, suppliers with the lowest freight tonnage tend to rely more on the CFS (the dots in the figure).

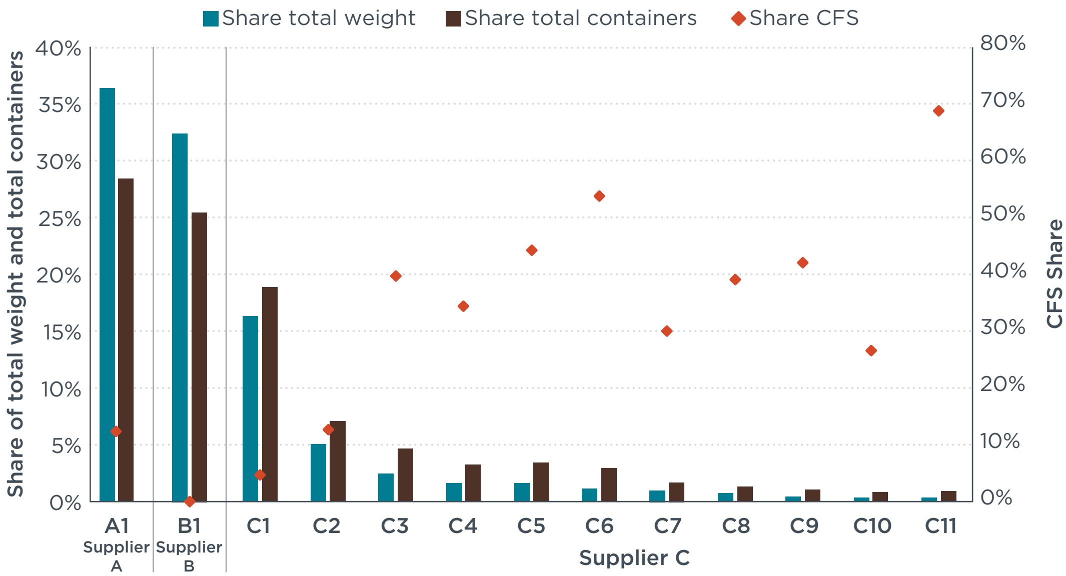


Figure 7. Freight amounts by factory and supplier in China

MARINE

The marine segment is the longest in the supply chain. Container ships depart from the Port of Shenzhen and travel approximately 12,000 km along the trans-Pacific eastbound trade route to get to the Ports of Los Angeles and Long Beach. The eastbound route is usually direct without stops, whereas westbound ships tend to stop at a few ports (e.g., Seattle, Busan, Shanghai) on the way back to Shenzhen. The Port of Shenzhen ranks third and the Port of Los Angeles 17th among the world's top container ports by volume as of 2017 (UNCTAD, 2018). Both ports are located in highly populated areas and are a major source of local air pollution. The Ports of Angeles and Long Beach are landlord ports, meaning that the Port Authority owns and manages the port area, and makes facilities available to terminal operators through concession agreements. The Port of Shenzhen is a joint public-private enterprise.

The study boundary for the marine segment starts when container ships load products at the Port of Shenzhen and stops when ships finish unloading at the Ports of Los Angeles and Long Beach. As indicated in the previous chapter, port operations are beyond the scope of this study except for ship emissions at berth and anchor. The marine segment can be disaggregated into three sub-segments with different characterizations of ship activities:

» **Port/anchorage segment.** Ships can wait at designated anchorages for available berths to load and unload cargo. Propulsion engines are usually shut down, but auxiliary engines and auxiliary boilers are still on to maintain operations. Depending on port operations, this process can take anywhere from a couple of hours to a few days. Container ships do not normally spend time at anchorage as they tend to have a fixed arrival schedule. This, however, can change when ports are seriously congested, as was the case for the Port of Long Beach around 2014 (Transport Medallion & Logistics, 2017).

» **Voyage segment.** Maintaining optimum speed on the open sea requires a high rate of fuel burned using the ship's main propulsion and auxiliary engines. Auxiliary boilers are typically shut down during this part of the voyage.

» **Transition segment.** Ships transit in or out of port or anchorage at reduced speeds.

Based on THD data, in 2017, products were shipped in 103 unique container ships with an average capacity of about 10,000 TEUs. Ships of that capacity generally fall into the Neopanamax size category, which ranges from 10,000–14,500 TEUs (Figure 8).

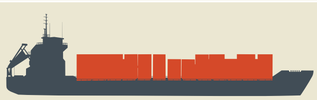
	Container ship size category	Capacity (TEUs)	Length (m)	Draught (m)	Example ship
	Small feeder	Up to 1,000	105	6.5	XIANG LING
	Feeder	1,001-2,000	169	8.4	CMA CGM TANGER
	Feedermax	2,001-3,000	196	11	SAFMARINE NIMBA
	Panamax	3,001-5,100	294	14	MSC FEDERICA
	Post-panamax	5,101-10,000	299	15	MSC ALTAMIRA
	Neopanamax	10,001-14,500	338	16	MAERSK ALGOL
	**Average ship deployed by THD**	10,107	339	15	
	Ultra large container vessel	14,501 and higher	366	16	COSCO SHIPPING ALPS

Figure 8. Container ship size categories and average ship deployed by THD

U.S. DRAYAGE

Once at the Ports of Los Angeles and Long Beach in Southern California, containers are unloaded at one of seven terminals. Because the terminals are just a few kilometers apart, this analysis considers a single origin and uses a middle point within the port area. At the terminals, drayage trucks receive containers and take them to either the transload facility (TSLD) 30 km north of the port, or to the Mira Loma stocking distribution center (SDC) 100 km away from the port (Figure 9). THD ships a larger share of freight through the TSLD, which is considerably closer than the Mira Loma distribution center. This reduces travel activity and associated emissions. In the TSLD, cargo is broken down and combined with other products to create full loads before being shipped to other SDCs and rapid deployment centers (RDCs). The TSLD has the capacity to store products temporarily while consolidation takes place, but it does not hold inventory like SDCs do.

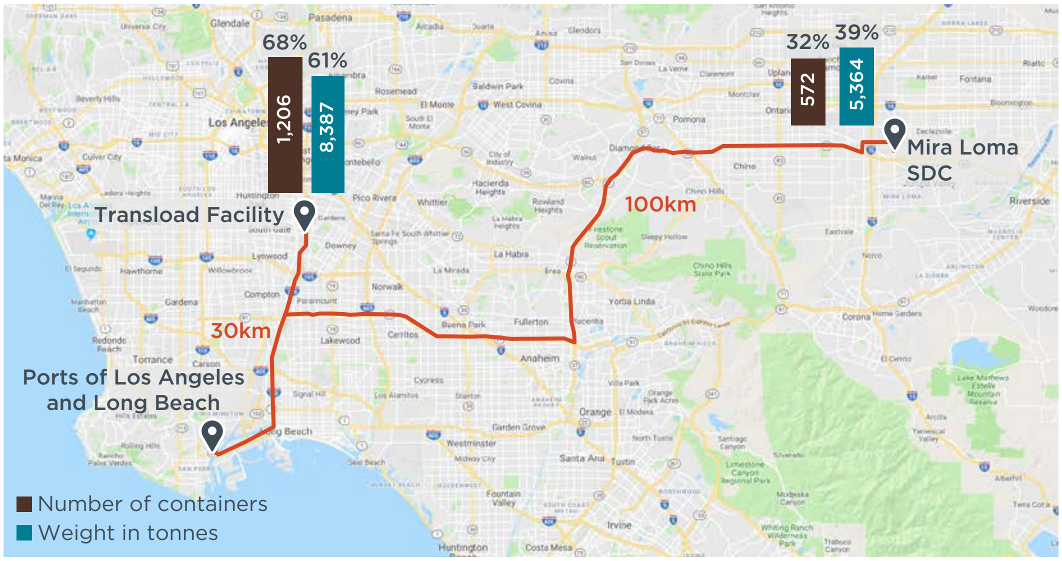


Figure 9. U.S. drayage node locations and share of containers and weight. Routes are shown for illustrative purposes only. Even assuming alternate routes, differences in distance traveled would not impact the results significantly. *Source*: Google Maps.

The share of containers sent to the TSLD or Mira Loma SDC varies by supplier (Table 3). Most containers with cargo from suppliers A and C are routed to the TSLD because they contain cargo from multiple suppliers and require deconsolidation. Because containers from supplier B are dedicated, they do not require deconsolidation and instead are mostly routed directly to the SDC.

Table 3. Summary of U.S. drayage freight movements by supplier

Supplier	Share of containers by supplier	Destination	Distance from port (km)	Total containers	Share of containers by destination (%)	Total weight (tonnes)	Share of weight by destination (%)
Supplier A	28%	Mira Loma SDC	100	120	24%	1,127	23%
		Transload	30	386	76%	3,876	77%
Supplier B	46%	Mira Loma SDC	100	418	92%	4,040	91%
		Transload	30	35	8%	413	9%
Supplier C	25%	Mira Loma SDC	100	34	4%	197	5%
		Transload	30	785	96%	4,098	95%
Total	**100%**	**Mira Loma SDC**	**100**	**572**	**32%**	**5,364**	**39%**
		Transload	**30**	**1,206**	**68%**	**8,387**	**61%**

U.S. INLAND

This segment involves shipments from the TSLD to distribution centers, including four SDCs and seven RDCs in 13 U.S. states (Figure 10). SDCs are THD's legacy distribution centers. They aggregate products from suppliers, hold inventory, and ship truckloads to stores. THD modernized its supply chain to speed delivery times and better serve increasing e-commerce demand. RDCs, cross-docking facilities that are key in this modernization process, sort and combine loads from multiple origins into full truckloads that are dispatched the same day to stores. RDCs do not hold inventory and thus require complex planning and demand forecasting to ensure freight is always flowing through the network.

This is the longest land-based transportation segment. With a weight-adjusted distance of 1,350 km, it is second only to the marine segment. This is also the only segment where rail is used. Our analysis subdivides the distribution centers based on distance from the TSLD:

» Short distance (70–100 km): one SDC and two RDCs (truck shipments).
» Medium distance (~550 km): one SDC and two RDC (truck shipments).
» Long distance (more than 2,300 km): two SDCs and three RDCs (rail shipments).

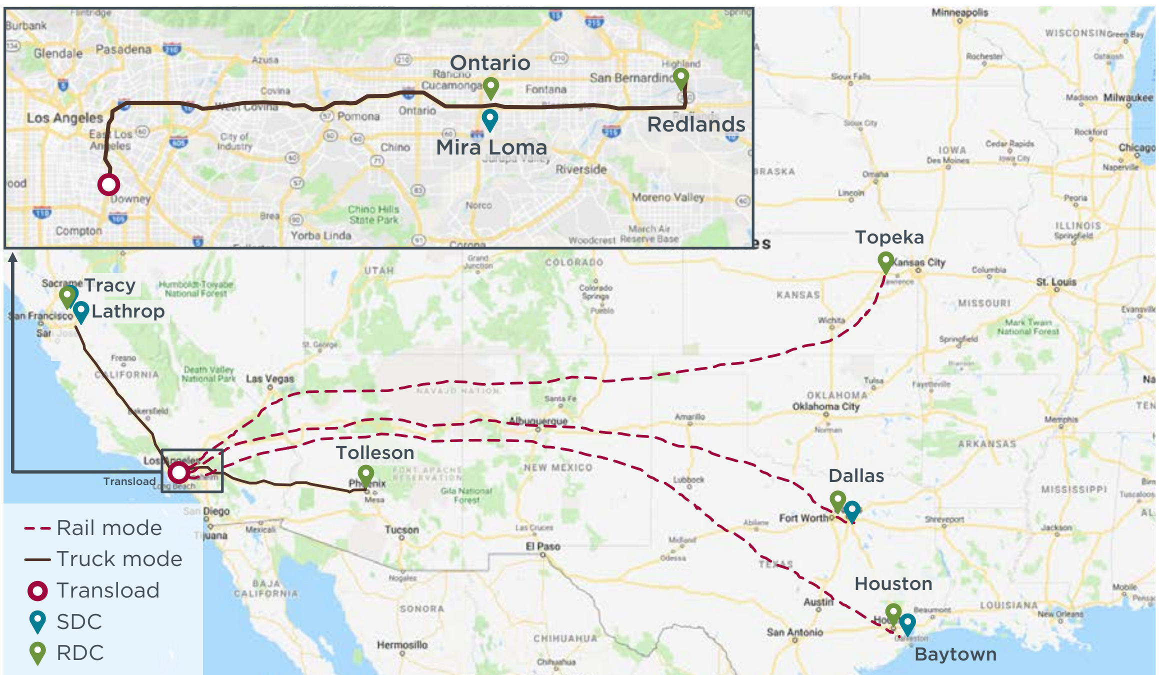


Figure 10. SDC and RDC network and transportation modes. *Source*: Google Maps.

Because the TSLD aggregates cargo from different suppliers, cargo from suppliers A, B, and C is shipped in smaller batches in trailers and/or railcars to SDCs and RDCs with products from other suppliers. Because this study is limited to the impacts of products from suppliers A, B, and C, the analysis puts a special emphasis on calculating shipment weight specific to those suppliers. This is so that truck and rail emissions and fuel consumption can be allocated accordingly.

Table 4 presents key indicators for SDCs and RDCs receiving freight. Although the total weight shipped is evenly divided between truck and intermodal routes, the intermodal routes account for more than 90% of total freight activity in terms of millions of tonne-kilometers. The Dallas and Baytown SDCs account for slightly more than half of total freight activity. This is due to the large gap between truck and intermodal route distances—there are no SDCs or RDCs between 600 km and 2,300 km.

Table 4. Summary of U.S. inland freight activity by SDC and RDC

Mode	DC	Distance from TSLD (km)	Total weight (tonnes)	(%)	Total freight activity (million tonne-km)	(%)
Intermodal	SDC - Dallas	2,311	1,259	15%	2.91	26%
	SDC - Baytown	2,547	1,160	14%	2.95	27%
	RDC - Houston	2,492	841	10%	2.10	19%
	RDC - Dallas	2,310	594	7%	1.37	12%
	RDC - Topeka	2,510	297	4%	0.75	7%
	Total Intermodal	**2,428**	**4,151**	**51%**	**10.08**	**91%**
Truck	SDC - Mira Loma	75	1,560	19%	0.12	1%
	SDC - Lathrop	542	584	7%	0.32	3%
	RDC - Ontario	76	575	7%	0.04	0%
	RDC - Redlands	107	527	6%	0.06	1%
	RDC - Tolleson	585	428	5%	0.25	2%
	RDC - Tracy	541	328	4%	0.18	2%
	Total Truck	**240**	**4,002**	**49%**	**0.96**	**9%**

SDC/RDC TO STORE

This segment includes shipments from SDCs and RDCs to 622 stores in the western United States (Figure 11). Stores in the eastern United States are served by other ports and are outside the scope of this study. All shipments are moved in 53-foot dry van trucks.

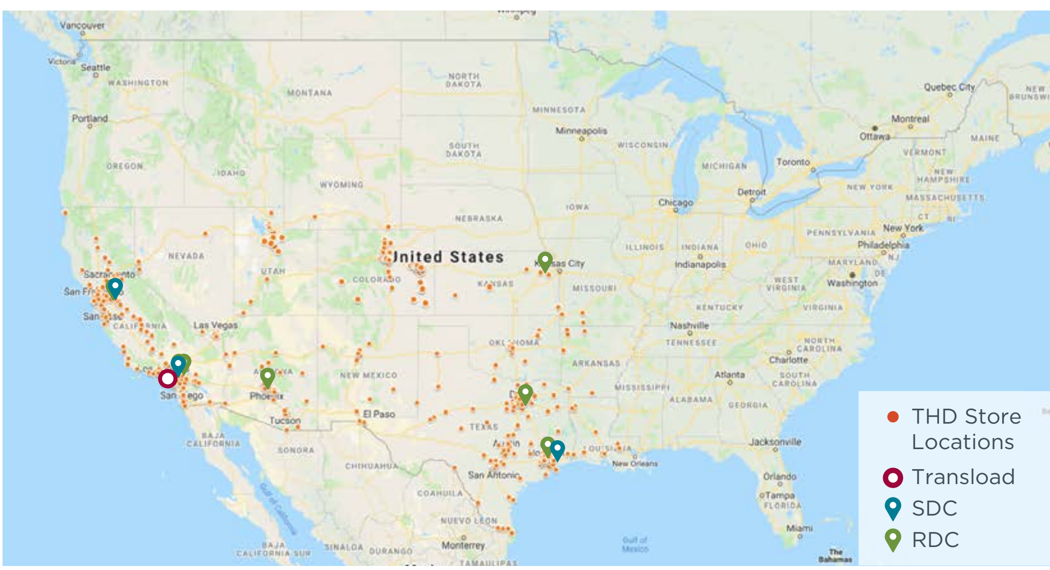


Figure 11. Distribution of THD stores included in the study. *Source*: Google Maps

Because SDCs can hold inventory, they are normally used for imported products, and this explains their larger share of freight activity in the data sample (Table 5). As cross-docking facilities, RDCs receive and sort incoming freight from different vendors and ship outbound truckloads to stores. The higher number of RDCs explains the shorter weighted distances to stores.

Table 5. SDC and RDC network outbound indicators

Distribution center		Outbound weight (tonnes)	Average distance to stores (km)[a]	Total freight activity (tonne-km)
SDC	Baytown	1,160	209	242,223
	Dallas	1,259	376	473,238
	Mira Loma	6,924	316	2,190,836
	Lathrop	584	116	67,760
	SDC Total	**9,927**	**300**	**2,974,057**
	SDC Share	**74%**	**—**	**79%**
RDC	Dallas	606	146	88,523
	Houston	848	170	144,116
	Ontario	515	107	55,018
	Redlands	524	389	204,126
	Tolleson	431	143	61,626
	Topeka	299	702	210,152
	Tracy	330	100	32,802
	RDC Total	**3,554**	**224**	**796,362**
	RDC Share	**26%**	**—**	**21%**

[a] Average distance adjusted by weight shipped to each store.

CHAPTER 4. **STRATEGY CHARACTERIZATION**

This study adapts the Avoid-Shift-Improve (A-S-I) approach as an analytical framework. A-S-I incorporates all elements of transportation system efficiency. Many multilateral development banks, the International Energy Agency, the German Society for International Cooperation, the 68-member Partnership on Sustainable Low Carbon Transport, and other institutions use it for analysis and decision-making in transportation projects, programs, and policies (Dalkmann & Brannigan, 2007). Here, the three elements refer to clean and efficient logistics, modes, and equipment:

- **Clean and efficient logistics** strategies aim to optimize freight activity and **avoid** inefficiencies. These strategies focus on system/network efficiency, not necessarily to reduce freight activity, but to increase vehicle utilization, reduce empty kilometers, and optimize routing, among other enhancements.
- **Clean and efficient modes** strategies promote the reduction of vehicle energy and emissions by **shifting** to modes with lower energy and emissions intensity. These strategies commonly include switching freight from trucking to rail, inland waterways, or short sea shipping, and from air to marine.
- **Clean and efficient equipment** strategies involve **improvements** to reduce the energy consumption and emissions intensity of transportation equipment and fuels. First, this can be done by incorporating cleaner and more-efficient technologies such as powertrain electrification, waste heat recovery, aerodynamic devices and low-rolling resistance tires on trucks, emission control technologies, and vessel technologies to improve engine and thrust efficiency and ship hydro- and aerodynamics. Second, environmental performance can be improved by changing the way equipment is operated; more-efficient driving practices for trucks and slow steaming for ships are two ways to do this. Finally, freight operations can rely on cleaner fuels like ultra-low sulfur fuels, biofuels, and electrification.

Table 6 categorizes the strategies analyzed in this study into these three types. The A-S-I elements are also described in more detail below.

Table 6. Strategies evaluated in each scenario and supply chain segment

Strategy type	Strategy	China drayage				Marine				U.S. drayage				U.S. inland				SDC to store				RDC to store			
		Green	*Green Plus* (ST)	*Green Plus* (MT)	*Green Plus* (LT)	*Green*	*Green Plus* (ST)	*Green Plus* (MT)	*Green Plus* (LT)	*Green*	*Green Plus* (ST)	*Green Plus* (MT)	*Green Plus* (LT)	*Green*	*Green Plus* (ST)	*Green Plus* (MT)	*Green Plus* (LT)	*Green*	*Green Plus* (ST)	*Green Plus* (MT)	*Green Plus* (LT)	*Green*	*Green Plus* (ST)	*Green Plus* (MT)	*Green Plus* (LT)
Clean and efficient logistics	Cargo consolidation (CFS)	●								●															
	Cube optimization	●								●				●				●				●			
	Transloading (network reconfiguration)									●															
	Floor loading	●								●				●				●				●			
	Shore power					●	●	●	●																
	Schedule optimization (port and ship)					●	●	●	●																
Clean and efficient modes	Truck to rail															●	●								
	Transloading (container switch)													●											
	Move to larger container ships[a]					●	●	●	●																
Clean and efficient equipment	Truck technology	●	●	●	●					●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
	Truck electrification			●	●							●	●							●	●			●	●
	Eco-driving training	●	●	●	●					●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
	Rail technology														●	●	●								
	Cleaner fuels[b]							●	●																
	Marine engine efficiency					●	●	●	●																
	Vessel operations (slow steaming, weather routing)					●	●	●	●																
	Vessel thrust efficiency						●	●	●																
	Vessel aerodynamics								●																
	Emission control policies	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●

● *Green* ● *Green Plus* – short term (2020) ● *Green Plus* – medium term (2025) ● *Green Plus* – long term (2030)

[a] This strategy could also be categorized as a logistics strategy.

[b] Benefits from higher use of low-carbon fuels are not included, except for the marine sector, because of the uncertainty around their carbon savings and ability to produce sufficient amounts of truly sustainable biofuels in the timeframe of this study.

LAND-BASED STRATEGIES – CLEAN AND EFFICIENT LOGISTICS

The following strategies make freight activity more efficient by increasing vehicle utilization, reducing empty kilometers, and optimizing routing, among other enhancements. The parameters used to model each strategy are summarized in Table 7, below.

Cargo consolidation (consolidated freight station or CFS)

This strategy improves container utilization, particularly for low-volume shipments that do not maximize container volume (typically referred to as less than container load). A common way for companies to reduce shipping costs is to hire a third-party logistics provider (3PL) or freight forwarder to combine low-volume shipments into full container loads (FCLs). While this strategy might increase lead times because of waiting at the CFS, it often reduces the shipping costs of less utilized containers.

In the supply chain evaluated, 88% of the cargo is shipped as FCLs because of high cargo volume included in every purchase order from each supplier. The remaining containers are not FCLs when they leave the factory; they are thus consolidated with cargo from other Chinese suppliers at a CFS close to the Yantian terminal. This is the *Green* scenario and the parameters were obtained directly from THD. Figure 12 illustrates how a CFS improves container space utilization from outbound shipments.

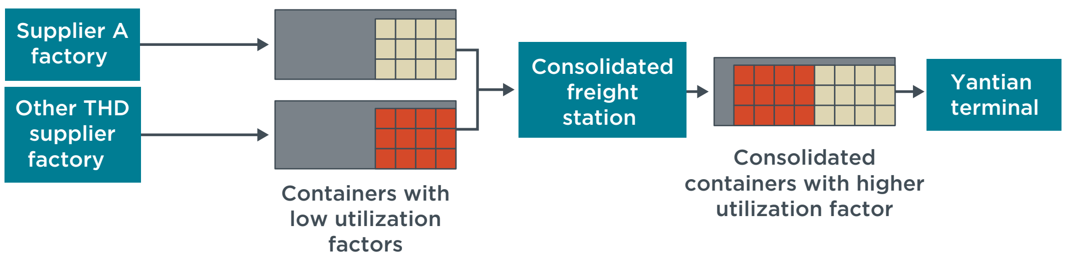


Figure 12. CFS operations

For the 12% of containers shipped to the CFS, this study disaggregated container utilization data before and after the CFS aggregation. To model the *Conventional* scenario, this analysis assumes that, instead of using the CFS, these 12% of containers are shipped directly from the factories to ports in a 20-foot container instead of a 40-foot container. This is a practice THD uses where it does not have a CFS, such as in freight that comes from Europe. While CFS improves container utilization, expanding CFS operations beyond the current 12% is not desirable, given the added time and costs associated with CFS operations. Therefore, the *Green Plus* scenario does not include expansion of CFS operations.

Cube optimization

Cube optimization maximizes the volume capacity of transportation equipment, including trailers, containers, and rail boxcars. It is often assumed this is a widespread practice by shippers and carriers, but equipment utilization in the shipping industry is below full capacity. This is caused by the following factors:

» **Cubed-out versus weighed-out equipment.** Equipment is limited by its maximum physical volume capacity and by legal weight limits. Companies moving very dense cargo will typically weigh-out, or reach weight limits, before using the full equipment volume capacity. Companies shipping less dense but voluminous cargo will typically cube-out, or reach volume capacity before reaching legal weight limits. This presents an opportunity to combine diverse cargo and optimize volume capacity and weight limits. Despite the operational challenges, companies with a wide array of products are better positioned to adopt this type of optimization.[5]

5 Although the three products evaluated have similar product density, they are mixed with other products that are not evaluated in this study.

- **Delivery time requirements.** Although the largest shippers have sophisticated systems to plan and forecast shipments in order to meet demand, market conditions such as unexpected time demands from customers might force shippers to move underutilized equipment.
- **Packaging practices.** Ultimately, the most relevant metric for equipment utilization is the total product units or payload being transported. Many companies have started to work closely with suppliers on strategies to reduce packed product volume and the weight of packaging materials while keeping the same level of protection and maneuverability.

Through container optimization software, THD predetermines the type and number of stock units to be loaded onto containers before a purchase order is generated and sent to supplier factories. This allows the company to fit as much as 10% more products in each container. THD's current average container utilization of 85% is the value in the *Green* scenario, and this study models the *Conventional* scenario by reducing the utilization factor to 75%. Increasing container utilization becomes harder as each is more fully optimized, and it might require other strategies besides software optimization. Some of these include co-loading or delaying shipments to aggregate more cargo. Therefore, this analysis does not consider further improvements in cube optimization in the *Green Plus* scenario.

Transloading

This strategy refers to transferring cargo between different equipment types in a TSLD. In addition to cargo sorting, consolidation, and deconsolidation, these facilities allow companies to hold cargo as needed to dispatch full truckloads. However, because transload operations are an additional segment in the supply chain, their use can increase delivery time, the risk of product damage, and labor costs. In the case of THD, however, transloading reduces land transportation activity because ocean shipping containers, at 40- or 45-feet long, are smaller than the 53-foot trailers or railcars used for domestic transportation.[6] In this case, the higher equipment capacity offsets the increase in transload costs, particularly as transportation distances increase.

In THD's supply chain, containers are transported from the Ports of Los Angeles and Long Beach to the TSLD, where cargo is aggregated and then sent to the inland SDCs and RDCs (Figure 13).

- **U.S. drayage.** Because the TSLD is closer to the port than the closest SDC (Mira Loma), transloading considerably reduces vehicle-kilometers traveled. This study assumes that, in the absence of transload operations—this is the *Conventional* scenario—trucks would go directly to the closest SDC, increasing travel distance from 30 km to 100 km. No further changes are considered in the *Green Plus* scenario.
- **U.S. inland.** In the *Green* scenario, cargo is transloaded from 40-foot containers to 53-foot trailers at the TSLD. In the *Conventional* scenario, this study assumes that 40-foot containers are used in the U.S. inland segment. No further changes are assumed in the *Green Plus* scenario.

6 As a reference, three 40-foot ocean containers are approximately equivalent to two 53-foot trailer/railcars.

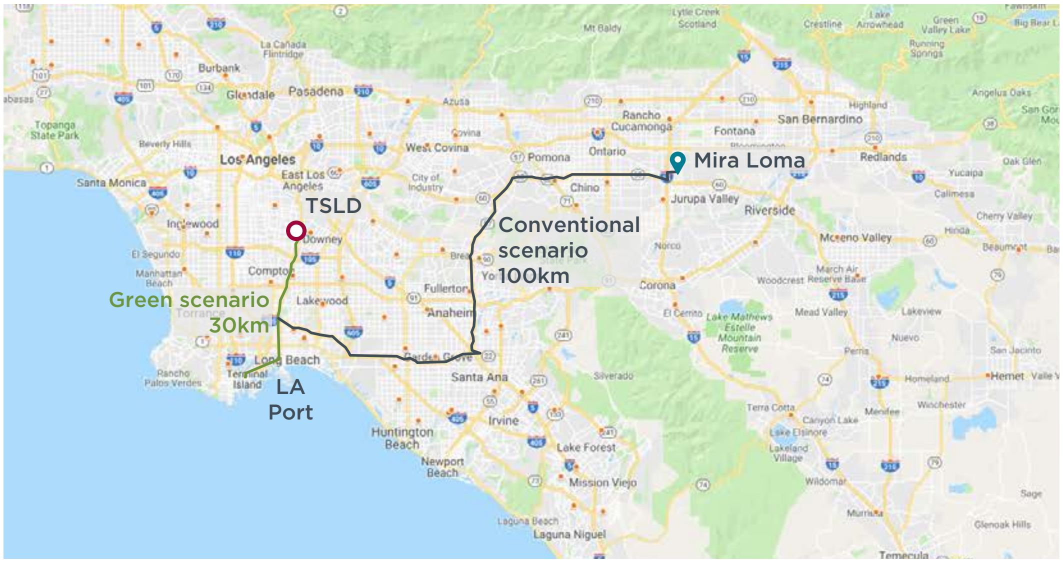


Figure 13. Transload operations. *Source*: Google Maps

Floor loading

Floor loading is closely tied to cube optimization and consists of loading a container with cargo from the floor up, rather than on pallets (Figure 14). Since pallets take space, eliminating them allows more product to fit. The main drawback of this strategy is that loading and unloading have to be done manually rather than with forklifts. This increases loading and unloading time and the risk of cargo damage.

Figure 14. Palletized versus floor-loaded

In the case of THD, several factors make floor loading an option to improve freight efficiency. These are large product quantities, long distances traveled by containers, and the ability to plan and forecast demand to manage inventories and delivery time requirements. THD realized an improvement in container utilization from floor loading of

4%, and this is the parameter used in the *Green* scenario for all transportation segments. No further improvements are considered in the *Green Plus* scenario.

Table 7. Clean and efficient logistics strategy parameters

Strategy	Parameter	Supply chain segment	Value *Conventional*	Value *Green*	Value *Green Plus*		
					Short-term	Medium-term	Long-term
Cargo consolidation (CFS)	Container type and utilization factor for 12% of containers shipped from China	China drayage	20-ft container; 45% utilization factor	40- or 45-ft containers; 86% utilization factor	Same as *Green* scenario		
Cube optimization	Percentage of container volume filled with THD products	All	75%	85%	Same as *Green* scenario		
Transloading (Logistics)	Distance from LA port to next node.	U.S. drayage	100 km (distance to closest SDC)	30 km (distance to TSLD)	Same as *Green* scenario		
Transloading (Mode)	Container capacity from TSLD outbound freight	U.S. inland	40-foot containers	53-foot trailers	Same as *Green* scenario		
Floor loading	Percentage of additional products fit into containers	All segments	—	4%	Same as *Green* scenario		

LAND-BASED STRATEGIES – CLEAN AND EFFICIENT MODES

Mode selection has historically been influenced by some combination of infrastructure availability, cost, lead time, reliability, and safety. These days, as leading companies start to place more value on corporate social responsibility and environmental goals, mode choices are becoming more complex. From an energy-efficiency perspective, cargo capacity is a key factor for mode performance. This is because larger capacity for similar equipment is typically associated with lower energy consumption per unit of product moved.

Two strategies to improve freight efficiency are to shift freight from trucking to intermodal rail (i.e., rail transport along the truck corridor, possibly supported by local truck drayage movements for "first/last mile") on land-based segments, and from air to marine on international operations. Because many international trade routes are long, water transportation is the most cost-effective mode for moving international freight. (One possible exception is highly valuable or time-sensitive goods.) Unsurprisingly, then, 80% of tonnage and 70% of the value of global trade is transported by water (ITF, 2017). In the case of land-based segments, switching from trucking to intermodal rail is generally more efficient as travel distances increase. However, the ability to switch to rail will also depend on the accessibility of infrastructure and the need for drayage movements in and out of railyards.

Truck to rail

Of all land-based segments, only the U.S. inland segment is suitable for rail operations because of the long distances involved. Shipments from SDCs and RDCs to stores require greater flexibility because each SDC and RDC delivers cargo to more than 50 stores, and this can only be achieved with trucks.

Table 8 indicates the modes associated with each origin-destination (O-D) pair in the U.S. inland segment, including those suitable for mode shift in each scenario. O-D pairs fall within three well-defined travel distance intervals, and THD already uses rail to move freight on the five longest routes (*Green* scenario). There is a significant difference between long-distance routes of more than 2,300 km and medium-distance routes of 500 km to 600 km, but the analysis assumes that all medium-distance routes can shift from trucking to rail in the medium- and long-term *Green Plus* scenarios. The analysis does not assume any mode shift between the *Conventional* and *Green* scenarios because it is unlikely that shipments of more than 2,000 km would be transported by trucks.

Table 8. Truck-to-rail parameters

Route type	Route	Travel distance (km)	Value *Conventional*	Value *Green*	Value *Green Plus*		
					Short-term	Medium-term	Long-term
Short-distance	TSLD–Mira Loma SDC	75	Same as *Green* scenario	Truck	Same as *Green* scenario		
	TSLD–Ontario RDC	76		Truck	Same as *Green* scenario		
	TSLD–Redlands RDC	107		Truck	Same as *Green* scenario		
Medium-distance	TSLD–Tracy RDC	541		Truck	Intermodal (medium/long)		
	TSLD–Lathrop SDC	542		Truck	Intermodal (medium/long)		
	TSLD–Tolleson RDC	585		Truck	Intermodal (medium/long)		
Long-distance	TSLD–Dallas RDC	2,310		Intermodal	Same as *Green* scenario		
	TSLD–Dallas SDC	2,311		Intermodal	Same as *Green* scenario		
	TSLD–Houston RDC	2,492		Intermodal	Same as *Green* scenario		
	TSLD–Topeka RDC	2,510		Intermodal	Same as *Green* scenario		
	TSLD–Baytown SDC	2,547		Intermodal	Same as *Green* scenario		

LAND-BASED STRATEGIES – CLEAN AND EFFICIENT EQUIPMENT

Clean and efficient equipment strategies reduce the energy consumption and emissions intensity of transportation through better technologies, operational improvements like eco-driving, and cleaner fuels.

Truck technology

The truck technologies considered in this study aim to reduce fuel consumption and emissions. Technologies that are applicable to internal combustion engine (ICE) trucks have been tested extensively, and there is consequently more certainty about their impacts and future trends (Rodriguez, Muncrief, Delgado, & Baldino, 2017). Examples of technologies considered in this analysis include those improving engine, transmission, and driveline, hybrid systems, lightweight materials, as well as aerodynamic devices and low-rolling resistance tires. Technologies to make truck platooning (i.e., linking two or more trucks in a convoy) feasible were outside the scope of this study because of safety concerns. The potential impacts of electrification are evaluated under a separate strategy, given the uncertainty about future trends and implementation across the different segments of the supply chain.

Truck fuel-efficiency technologies reduce the total amount of fuel burned and therefore decrease CO_2 emissions. Emission control technologies—which include selective catalytic reduction (SCR) and diesel particulate filters (DPF)—and low-sulfur fuels can virtually eliminate tailpipe local pollutants such as NO_x and $PM_{2.5}$. This report captures the impacts of truck technology through two parameters: truck fuel efficiency in liters per 100 km, or L/100km, and truck emission factors in grams per kilometer, or g/km, for different local pollutants (Table 9). These values were obtained or estimated using a combination of real data for heavy-duty truck fleets in China and the U.S. and research on truck technology potential. Appendix A describes the sources of truck technology parameters used.

Truck efficiency and emissions for THD's current *Green* scenario operations in the U.S. are based on SmartWay data, which is reported by almost 3,500 U.S. carriers and logistics providers. To protect carrier data confidentiality, SmartWay public data aggregates carriers in five bins based on their relative emissions intensity of CO_2, NO_x, and $PM_{2.5}$ per tonne-mile. THD's shipment data included specific carrier information for each shipment in U.S. land-based segments, and the EPA calculated the weighted average emissions intensity for each segment. THD prioritizes the most efficient carriers and provides incentives to carriers performing in top bins in the SmartWay program. For Chinese carriers, this study estimates truck fuel efficiency based on the characteristics—engine size, gross vehicle weight rating (GVWR), average payload, and fuel type—of the average truck hired by THD suppliers in China. For local pollutants, it is assumed that trucks used by THD suppliers meet China V emission standards; this is based on interviews with local truck carriers.

With respect to the *Conventional* scenario, this study assumes that THD used an average U.S. carrier before joining the SmartWay program. Because it is likely that SmartWay carriers, even those in the least-efficient bins, already perform better than non-SmartWay carriers, this study assumes the use of the least-efficient SmartWay bin (Bin 5) in U.S. segments. For Chinese carriers, it is assumed that they meet China fuel consumption standard stage 1, based on engine size, GVWR, average payload, and fuel type. Emission factors of local pollutants for trucks in China are based on an ICCT analysis of testing conducted by Tsinghua University and the Vehicle Emission Control Center (VECC)-MEE (Cui et al., 2018).

In modeling the *Green Plus* scenario, this study relied on research suggesting that technology packages for large tractor-trailers equivalent to U.S. Class 8 can improve fuel efficiency by 50% in the United States by 2027 from a 2015 baseline; that is equivalent to a 5.6% annual improvement (Delgado, Miller, Sharpe, & Muncrief, 2016). Improvements for drayage trucks in the United States and China were adjusted downward to a 2.2% annual improvement to account for lower speeds. For this potential to be realized, current HDV fuel efficiency and GHG regulations adopted in the United States, Canada, China, and Japan need to be strengthened. For local pollutants, the study assumes that increasingly more trucks meet China VI or U.S. EPA 2010 emissions standards. In addition to more-stringent limits on emissions, these standards also introduce important requirements to ensure that legal limits correspond with the emission reductions achieved in the real world (Yang & He, 2018).

Table 9. Truck technology parameters

Strategy	Parameter	Segment	Value *Conventional* (increase from *Green* scenario)	Value *Green*	Value *Green Plus* (reduction from *Green* scenario)		
					Short-term	Medium-term	Long-term
Truck technology	Truck fuel consumption (L/100km in *Green* scenario)	China drayage	12%	37	-6%	-16%	-27%
		U.S. drayage	12%	37	-6%	-16%	-27%
		U.S. inland	12%	34	-11%	-31%	-55%
		SDC to store	12%	35	-11%	-31%	-55%
		RDC to store	12%	35	-11%	-31%	-55%
	NO_x emission factor (g/km in *Green* scenario)	China drayage	1.4 times	6.5	-89%	-90%	-91%
		U.S. drayage	4 times	1.5	-6%	-16%	-27%
		U.S. inland	4 times	1.4	-11%	-31%	-55%
		SDC to store	4 times	1.4	-11%	-31%	-55%
		RDC to store	4 times	1.4	-11%	-31%	-55%
	$PM_{2.5}$ emission factor (g/km in *Green* scenario)	China drayage	12 times	0.03	-90%	-91%	-92%
		U.S. drayage	12 times	0.017	-6%	-16%	-27%
		U.S. inland	12 times	0.015	-11%	-31%	-55%
		SDC to store	12 times	0.016	-11%	-31%	-55%
		RDC to store	12 times	0.016	-11%	-31%	-55%

Truck electrification

Zero-emission vehicle (ZEV) technology plays a critical role in decarbonizing the transportation sector to meet global climate and health goals. Although there are already mature ZEV applications for light-duty vehicles, the timeline for more-widespread truck applications is longer. This is with the possible exception of urban delivery vehicles, where many pilot programs already exist. Experts agree that ZEV deployment will vary considerably by driving cycle—urban or highway—region, and technology (Moultak et al., 2017).

This analysis is conservative in that it assumes zero-emission trucks only for short- and medium-distance routes of less than 200 km in the *Green Plus* scenario. For the China drayage and U.S. drayage segments, the analysis assumes that 10% of trips are zero-emission in the medium term and 20% in the long term. For SDC/RDC to stores, the analysis assumes zero-emission trucks for routes of less than 200 km in the medium term and on routes of less than 400 km in the long term. Zero-emission trucks are not considered in the U.S. inland segment because all routes are long distance.

Table 10. Truck electrification parameters

Strategy	Parameter	Segment	Value *Conventional*	Value *Green*	Value *Green Plus*		
					Short-term	Medium-term	Long-term
Truck electrification	Share of trips by zero-emission trucks	China drayage, U.S. drayage	0%	0%	0%	10%	20%
	Maximum distance threshold for zero-emission trucks	SDC to store, RDC to store	—	—	—	200 km	400 km

Eco-driving training

Certain driving techniques and maintenance procedures ensure optimal truck energy and environmental performance (AECOM, 2016; Kurani, Sanguinetti, & Park, 2015). These include maintaining constant speeds, eliminating abrupt accelerations, and reducing hard braking and its associated energy waste. Training drivers to adopt these techniques and procedures can provide immediate benefits in terms of energy, emissions, and safety. In fact, carriers agree that improvements in driver behavior can result in higher efficiency gains than those from fuel-efficient technologies (Browning et al., 2017). Combining fuel-saving driving techniques with greener technologies can yield even greater fuel savings and emission reductions. (Recall that truck platooning was not considered in this study because of safety concerns.)

Eco-driving training can improve fuel consumption at a relatively low cost, particularly for those techniques where driver behavior plays a key role. There is high variability in terms of training results, with most studies finding 5%–15% gains. To achieve the maximum benefits, it is important to systematize training, continuously monitor driver performance, implement reward schemes, and leverage technology such as telematics for support and feedback.

Table 11 describes the most common driving techniques and maintenance practices included in eco-driving programs. Technology can support or even automate the adoption of some of these techniques. In the case of automatic tire inflation systems, a drop in tire pressure can increase rolling resistance, and this will, in turn, raise fuel consumption. Conducting regular tire pressure checks will ensure optimal tire pressure, and auto-inflation systems can forgo driver monitoring and intervention.

Table 11. Driving techniques and maintenance procedures in eco-driving training programs

Driving techniques	Maintenance procedures
• Gear selection (Green zone revolutions per minute) • Constant highway speed • Engine-braking/torque • Reduce idling • Route planning	• Lubricants/engine oil • Intake/exhaust system (DPF) • Engine cooling • Air compressors • Wheel alignment • Tires • Fuel filter systems • Aerodynamic devices (retrofit) • Electrical systems • Air conditioning

Because there are many ways to pursue this strategy, this analysis considers eco-driving training as a package of individual techniques, maintenance practices, and technologies that yield different levels of improvement as programs make gains in systematization and professionalization. Table 12 includes the assumed percentage improvements for each scenario.

Table 12. Eco-driving training parameters

Strategy	Parameter	Segment	Value *Conventional*	Value *Green*	Value *Green Plus*		
					Short-term	Medium-term	Long-term
Eco-driving training	Percentage improvement over truck's conventional fuel consumption	All land-based segments with truck operations	0%	3%	5%	5%	5%

Rail technology

Moving freight by rail is considerably more energy efficient than moving it by truck, particularly for higher-density commodities on longer trips. A detailed analysis of 23 freight corridors in the United States found that rail was 1.9–5.5 times more energy efficient than trucks (ICF International, 2009). Despite its energy benefits, however, rail could increase emissions of local pollutants because of the 30–40 years of useful life for diesel locomotives, which favors engine retrofitting over replacement with newer technologies (Gladstein, Neandross & Associates, 2013a). In addition, trucks are becoming increasingly cleaner over time.

Promoting the adoption of cleaner rail technologies will help to ensure that climate and energy benefits are not offset by an increase in local pollutant emissions (Natural Resources Defense Council, 2015). The analysis considers three different rail technology alternatives (Table 13):

» **Tier 2.** This U.S. emissions standard for locomotive engines is the baseline for performance in this study. Although some trains already meet the newest Tier 4 (see below) standards, most locomotives still operate at Tier 2 levels. This study assumes no variations in rail technology between the *Conventional* and *Green* scenarios.

» **Tier 4.** This is the latest and cleanest standard, and it applies to U.S. locomotives that entered production in 2015 (Rail Transportation and Engineering Center at the University of Illinois at Urbana-Champaign [RailTEC], 2016). This study assumes an accelerated transition toward widespread Tier 4 technology for the *Green Plus* medium-term scenario. The largest benefit is expected to be a reduction in local pollutants, since this standard does not have an impact on energy consumption. However, to the extent that PM is reduced, black carbon, a potent climate pollutant, is also lowered. This generates climate benefits.

» **Tier 4 + 10% electric.** Electrification is an alternative for decarbonizing rail freight, but only in the long run. Powering locomotives with electric engines presents significant challenges that must be addressed before it is feasible (Cambridge Systematics, 2012; RailTEC, 2016). High uncertainty surrounds future trends and how this technology will evolve. The analysis therefore evaluates the impact of electrifying 10% of total rail freight and keeps Tier 4 for the remainder of the *Green Plus* long-term scenario. The 10% assumption is roughly equivalent to the electrification of rail within the Los Angeles metropolitan area. A study commissioned by the Southern California Association of Governments which sought to determine the feasibility and costs of rail electrification, and to develop an implementation plan for it, showed that it was feasible from a technological perspective (Cambridge Systematics, 2012).

Table 13. Rail technology parameters

Strategy	Supply chain link	Parameter	Value *Conventional*	Value *Green*	Value *Green Plus*		
					Short-term	Medium-term	Long-term
Rail technology	U.S. inland	Technology alternatives	Tier 2	Tier 2	Tier 2	Tier 4	Tier 4 + 10% EV

MARINE STRATEGIES

To reduce energy consumption and emissions along the marine segment, two broad sets of strategies are considered. One group targets the reduction of bunker fuel consumption via increased fuel efficiency and alternative propulsion concepts, including electrification and using low-carbon synthetic fuels like hydrogen and ammonia. This would consequently reduce GHG emissions. While upstream emissions from electricity and hydrogen production are not zero, the analysis here considers electrification and hydrogen zero-emission strategies because only tailpipe emissions are considered.

The second group of strategies includes vessel emission standards, which drive down air pollution emitted per unit of fuel consumed. This study focuses on standards for oceangoing vessels set by the International Maritime Organization (IMO). This analysis breaks down these strategies into the three A-S-I types, consistent with the approach adopted for land-based strategies. The assumptions for each are summarized in Table 14.

» **Clean and efficient logistics.** These are strategies to reduce unnecessary fuel consumption that results from uncoordinated schedules or long periods spent at berth loading and unloading cargo. Better-coordinated schedules can reduce the so-called anchorage time of ships waiting for available berths to as low as zero. Additionally, ships can plug into dockside electricity to avoid using liquid fuel while at berth. Regulations at port cities will gradually mandate that ships increase the use of shore power at berth, and it is anticipated that, in the long-term *Green Plus* scenario, all emissions at berth will be reduced to zero. These strategies are all mature, but more work is needed to increase adoption.

» **Clean and efficient modes.** These are strategies to move cargo to more-efficient carriers and ships. The larger the container ship, the fewer pollutants emitted per unit of transport work performed. The average size of the current THD ship fleet is about 339 meters in length, but the largest container ship in service today is 18% larger at 400 meters.

» **Clean and efficient equipment.** These are technological strategies for current ships that carry THD's products, and they include a large number of potential technologies that are at different levels of maturity and market penetration. The IMO has put in place an efficiency improvement target for new build ships, the Energy Efficiency Design Index. It requires that the carbon intensity of newbuild ships be reduced by certain amounts over a set period of years (Hon & Wang, 2015). However, the shipping industry is expected to outpace the targets. Various types of technologies that could help achieve the IMO efficiency targets are shown in Figure 15. This analysis also considers emission control policies that could help reduce local pollutants from marine engines and operations and thus render health benefits. Such policies include the global sulfur limit to be enforced by the IMO starting in 2020, which will reduce SO_x emissions directly and $PM_{2.5}$ emissions indirectly from ships, and emission control areas (ECAs) where more-stringent SO_x and NO_x regulations are implemented. The Ports of Los Angeles and Long Beach are located within the North America ECA, which has a width of 200 nautical miles. It is expected that China will have a similar ECA in the future.

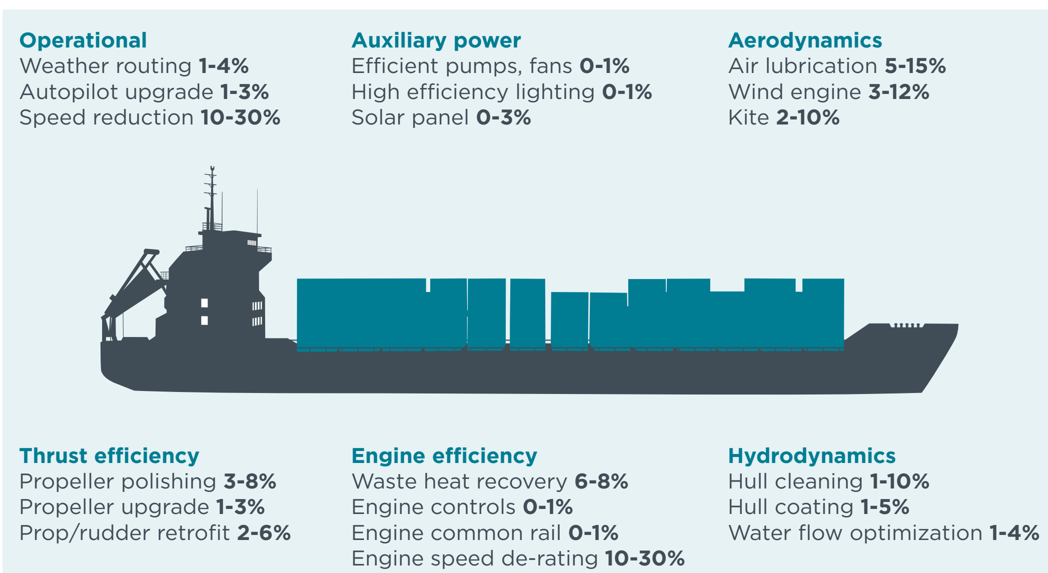


Figure 15. Potential energy and CO_2 savings from vessel efficiency strategies (Wang & Lutsey, 2013)

Table 14. Marine strategy parameters

Type	Details	Key parameters for assumption	*Conventional*	*Green*	*Green Plus* (short-term)	*Green Plus* (medium-term)	*Green Plus* (long-term)
Clean and efficient logistics	Schedule optimization	Anchorage time/hours	20	11	7	3	0
	Shore power	Plug-in rate: Ports of LA & LB	0.2	0.5	0.8	1	1
		Plug-in rate: Port of SZ	0	0	0.5	0.8	1
Clean and efficient modes	Move to larger container ships	Ship size/meters	329	339	366	395	400
Clean and efficient equipment	Ship-side technology	Efficiency improvement rate	0	20%	40%	50%	55%
	Emission control policies: Within ECA: 1,000 parts per million (ppm) fuel sulphur content, Tier III NO_x requirement Outside ECA: 35,000 ppm fuel sulphur content prior 2020, 5,000 ppm post 2020; Tier II NO_x requirement		U.S. ECA	U.S. ECA	U.S. ECA; global sulfur limit	U.S. ECA; Global sulfur limit; China 100 nautical miles ECA	U.S. ECA; Global sulfur limit; China 200 nautical miles ECA

LOW-CARBON FUELS

Reducing the carbon intensity of transportation fuels is a long-term priority for the transportation sector. Unfortunately, accurately measuring the life-cycle carbon intensity of biofuels has been subject to controversy and uncertainty. While biofuel production can limit oil dependence, there is strong evidence that the liquid biofuels that have achieved the greatest market penetration to date will not deliver substantial net carbon savings compared with fossil fuels. This is because of indirect emissions from biofuel production, in particular land-use change. In some cases, the use of biofuels is likely to increase net carbon emissions. The biofuels with the best environmental performance—e.g., lignocellulosic and algal biofuels—have the least certainty about commercialization and deployment.

Although many regions have implemented biofuel mandates and subsidies, there is uncertainty about the carbon savings from biofuels and the ability to produce truly low-carbon fuels in the period covered in this study. For road transportation, alternatives such as electrification are likely to provide more verifiable emission reductions at a lower cost than these fuels. In order to avoid speculating based on the scant evidence, we do not assume further reductions in GHG emissions from road transport resulting from the use of biofuels.

Given the need for high-energy-density liquid fuels for long-range transport and the emission reduction targets under the IMO's initial GHG strategy, maritime shipping companies are increasingly interested in low-carbon marine fuels (Rutherford & Comer, 2018). For example, Mærsk Group is researching lignin-based fuel (Green Car Congress, 2013), CMA CGM is pilot-testing a residual and waste biofuel (gCaptain, 2019), and the Global Industry Alliance to Support Low Carbon Shipping was launched in 2017 (GloMEEP, 2017). These and similar developments could result in limited availability of low-carbon marine fuels within a decade.

A previous ICCT study (Searle & Malins, 2015) showed that the maximum plausible amount of low-carbon biomass that could be supplied for energy is around 90 exajoules

(EJ) annually in 2050, and all sectors would compete for this. Subsequent work (Searle, 2018) indicated that as much as 5 EJ of fuels from low-carbon biomass may be available for international shipping. This study assumes sustainable biofuels can reduce the carbon intensity of the marine segment by 10% in 2025 and 20% in 2030. Besides availability, biofuels have other environmental challenges, including land use change and water pollution, that are beyond the scope of this study.

CHAPTER 5. **RESULTS**

This chapter summarizes the energy, climate, and health impacts of emissions reduction strategies. First, the share of freight activity, energy consumption, and emissions by supply chain segment is presented. Following that are the aggregated results across the supply chain and, finally, more detailed analyses for each supply chain segment are presented.

OVERVIEW OF ENERGY AND EMISSIONS ACROSS THE SUPPLY CHAIN

Different segments of the supply chain have different energy and emission intensities. Figure 16 is based on results from the *Conventional* scenario and illustrates the share of freight activity, energy consumption, and CO_2 emissions of each supply chain segment. While marine represents more than 90% of freight activity, it accounts for just more than half of CO_2 emissions because moving freight by vessels is significantly more efficient than by other modes (also illustrated in Figure 16).

The U.S. inland segment is more efficient than the other land-based segments because it includes a combination of trucking and rail, the latter of which is more efficient for moving freight on a tonne-km basis. The China drayage segment is the least efficient because it relies on trucks with less-advanced technologies than their U.S. counterparts. The variations in energy and CO_2 intensities across the remaining U.S. land-based segments stem from a combination of truck technologies and operational practices such as truck size, technology, and utilization.

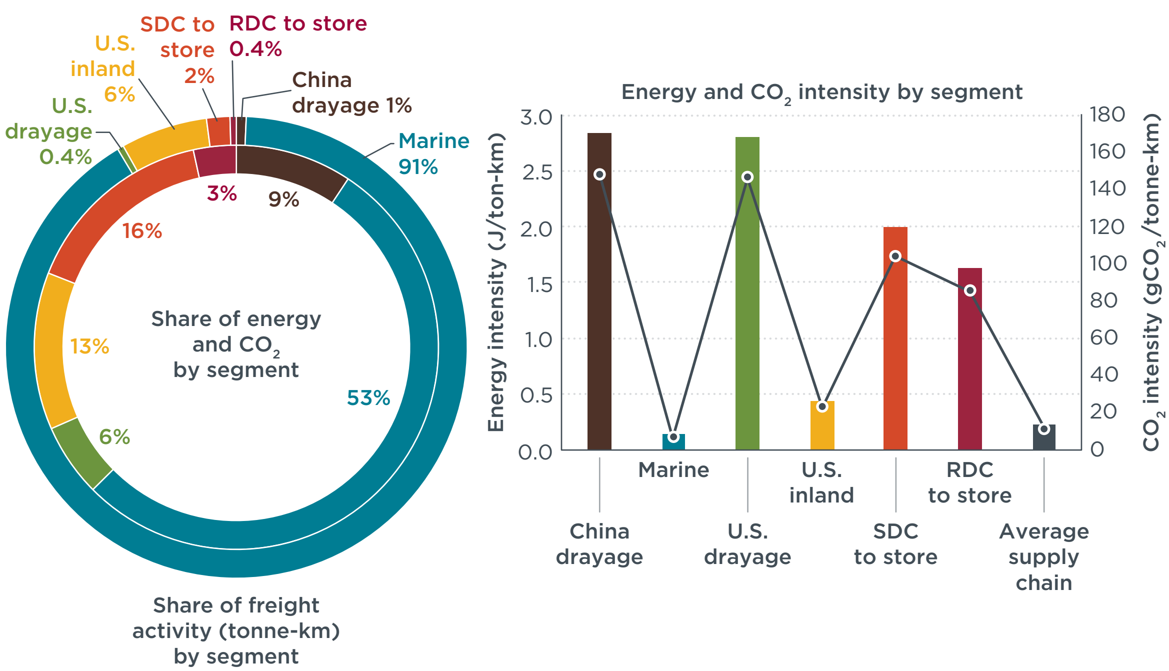


Figure 16. Left chart: Freight activity share (outer ring), energy/CO_2 share (inner ring); and right chart: energy intensity (lines) and CO_2 intensity (columns), all by supply chain segment under the *Conventional* scenario

The relative efficiency of marine does not carry over to local pollutants. The marine segment accounts for 96% of NO_x and 98% of $PM_{2.5}$ supply chain emissions (see Figure 17). This is primarily driven by the high sulfur content of marine residual fuels and the relative weakness of vessel emission controls when compared with diesel fuel and truck emission controls. Within the land-based segments, emissions intensity in the China and U.S. drayage segments is relatively higher because older trucks are typically used for drayage. Similarly, for energy efficiency, emissions intensity for the U.S. inland segment is lower because of higher-capacity equipment (trucks and rail).

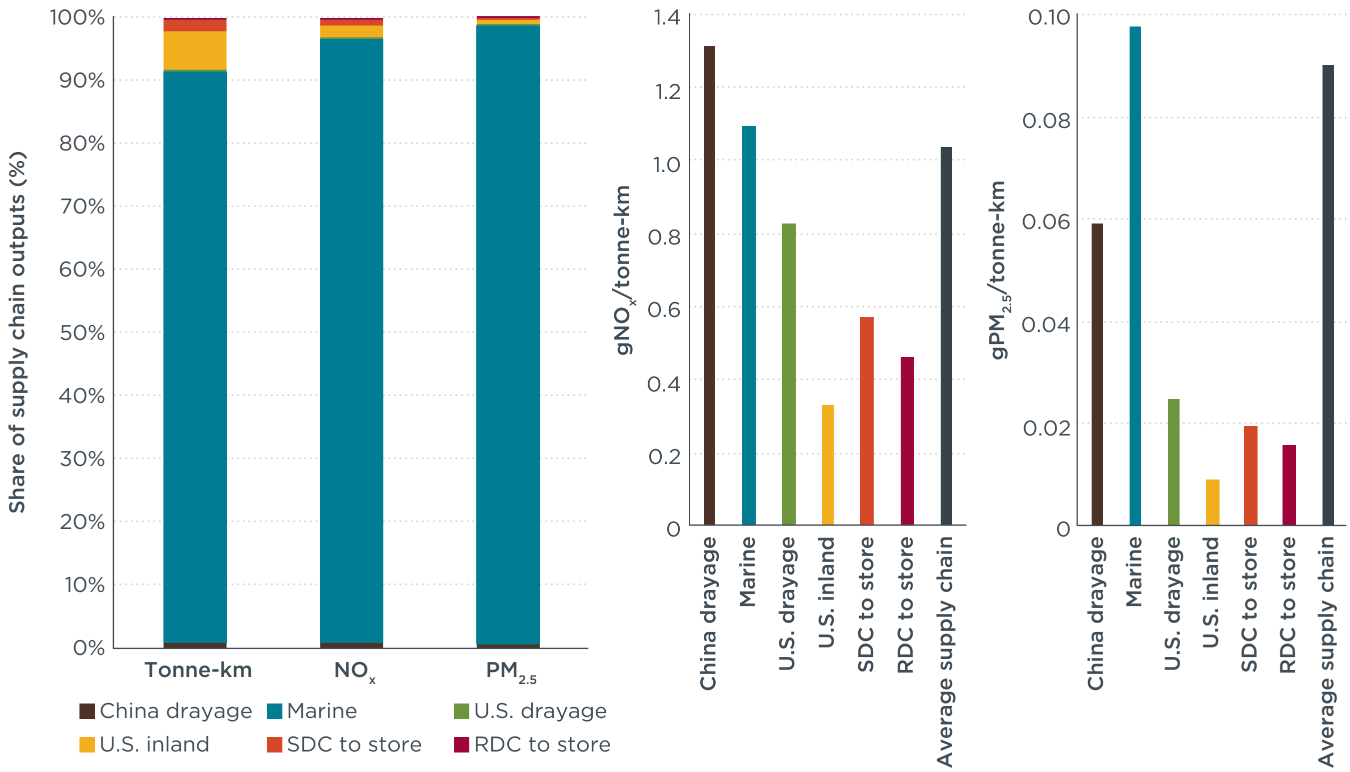


Figure 17. Freight activity, emissions share, and intensity by supply chain segment under the *Conventional* scenario

Figure 18 shows how energy and emission intensities are reduced in the *Green* and *Green Plus* scenarios as logistics, modal, and equipment strategies are deployed along the supply chain. Maximum reductions are on the order of 60%–85% for energy and CO_2, and reductions of local pollutants are even higher at more than 80% for land-based modes. This is because truck emissions controls are highly effective, in particular SCR systems for NO_x, DPFs for $PM_{2.5}$, and electric-drive systems with zero tailpipe emissions.

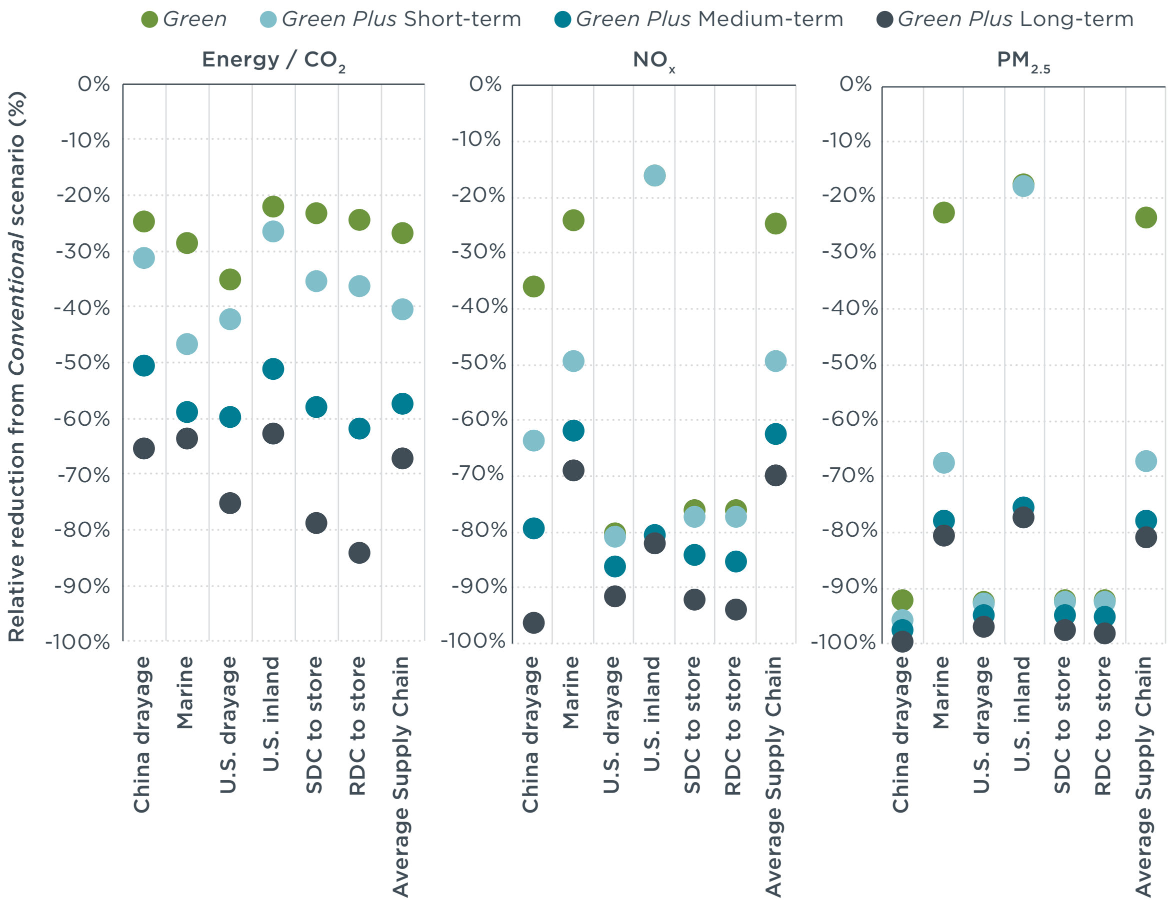


Figure 18. Reduction in energy and emissions intensities by scenario

ENERGY AND CLIMATE SUMMARY RESULTS

The *Green* scenario reduced supply chain energy use and CO_2 emissions by about 27% compared with the *Conventional* scenario (Figure 19). This can be understood as the difference in the supply chain energy and climate performance of leading companies versus today's business-as-usual industry practices. Although savings will vary in other industries and on other trade routes, these results estimate the savings possible if companies improve their supply chain efficiency. However, this is not meant to represent an upper bound of savings. These results also highlight the importance of conducting similar assessments for other types of companies, products, and trade routes so that more-comprehensive estimates of savings can be achieved.

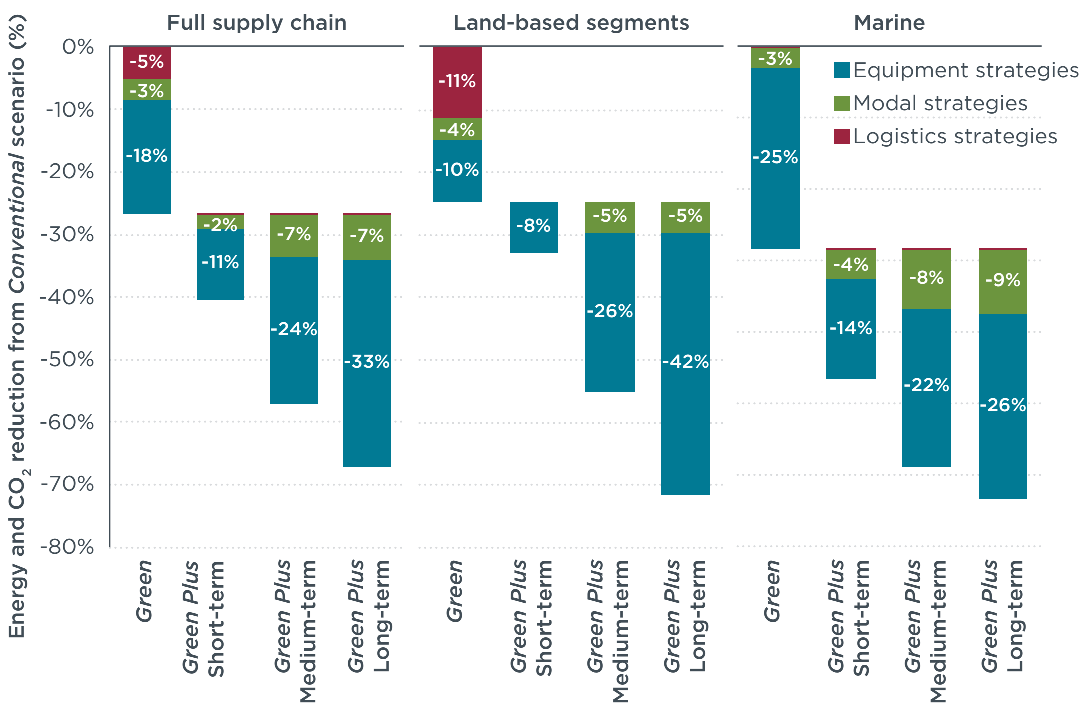


Figure 19. Energy and CO_2 emission reductions by segment and strategy type

Looking to the future in the long-term *Green Plus* scenario, energy consumption and CO_2 emissions can be reduced by 67% from the *Conventional* scenario; this is more than twice the savings in the *Green* scenario. These results highlight the enormous potential to further reduce energy consumption and carbon intensity from freight operations and, importantly, the estimates used are conservative. Because supply chain operations are intricate, this analysis does not include a full suite of future logistics and modal strategies in the *Green Plus* scenario in the same way that those are considered in the *Green* scenario. Estimates of future savings are primarily derived from technology strategies (the blue wedges in Figure 19) that can be more accurately modeled in future scenarios.

Figure 19 shows that savings are of the same order of magnitude between land-based segments and marine, for both the current *Green* scenario and future *Green Plus* scenario. However, while savings in the land-based segments from the *Green* scenario are roughly equivalent between logistics and equipment strategies—and relatively smaller from modal strategies—the marine sector relies heavily on equipment strategies and, to a lesser extent, modal strategies. Logistics strategies do not play a role in marine savings in this case, but cargo owners could opt for greener ports. As for future savings in the *Green Plus* scenario, marine relies on a combination of equipment and modal strategies, including the use of higher-capacity container ships, while land-based segments rely more heavily on equipment strategies.

HEALTH SUMMARY RESULTS

When compared with the *Conventional* scenario, strategies in the *Green* scenario reduced local pollutant emissions by 23%–25%, depending on the pollutant (Figure 20). Additionally, because of very effective emissions controls for transportation equipment, there is a lot of potential to reduce emissions even further in the future. Emissions in the *Green Plus* scenario are 70%–81% lower than in the *Conventional* scenario, depending on the pollutant, and a large majority of the current and future savings come from clean equipment and modes with higher capacity equipment.

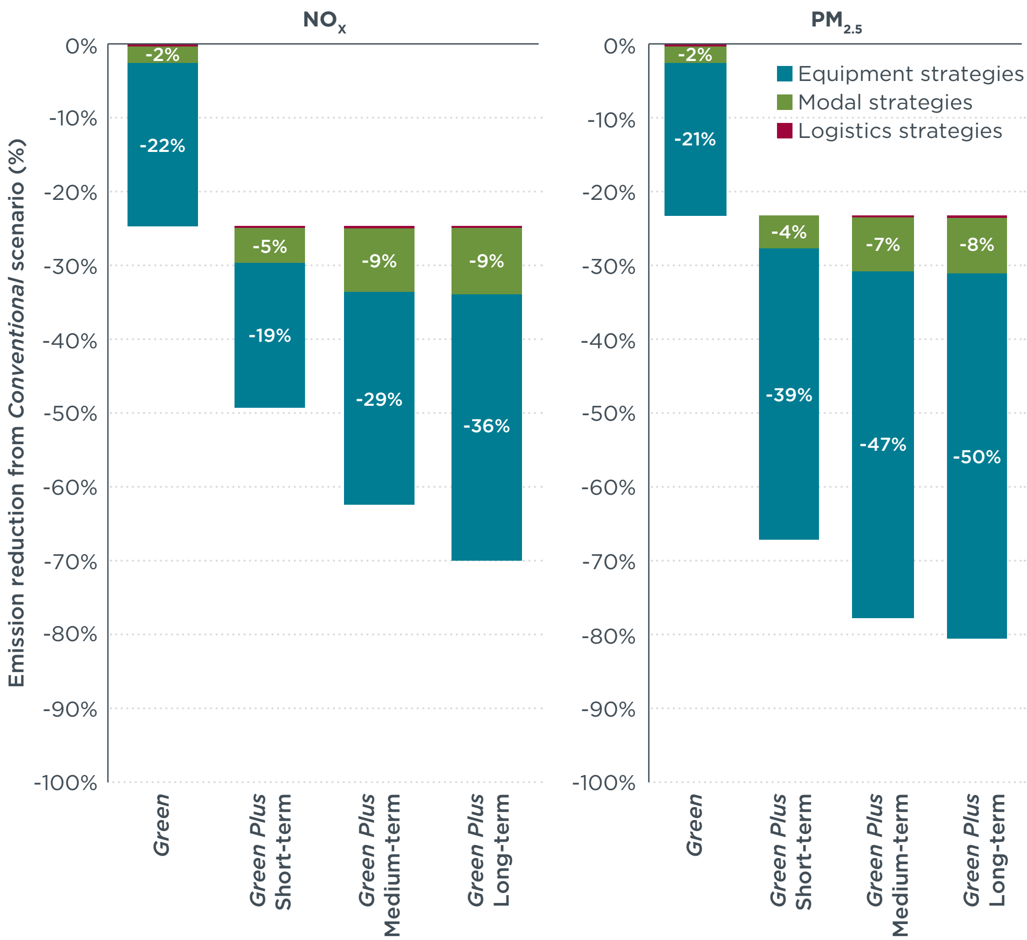


Figure 20. Total NO_x and $PM_{2.5}$ emissions savings by type of strategy

These findings are consistent with recent research highlighting the significant reductions that can be achieved using the best emission control technologies in trucks and ships. For example, SCR technology can reduce NO_x emissions by more than 80% and allows for engine tuning that reduces $PM_{2.5}$ by 75% with the use of a diesel oxidation catalyst (Chambliss et al., 2013). SCR technology has also been applied in ships to reduce NO_x

emissions by more than 90% (California Air Resources Board, 2018). DPFs have the potential to control 90%–95% of $PM_{2.5}$ from certain marine engine types. In ships, fuels with less than 1,000 ppm sulfur content can reduce $PM_{2.5}$ emission rates by about 90% (Mao, Chen, Comer, & Rutherford, 2019).

Because the marine segment emits more than 95% of the air pollutants in the supply chain, it is important to narrow the analysis to land-based segments.[7] Figure 21 illustrates how the general conclusion that equipment strategies are the best way to achieve the most health-related savings also applies to land-based segments. However, it also shows that logistics and modal strategies do contribute to health-related savings. This is by reducing transportation activity and through the use of more-efficient modes.

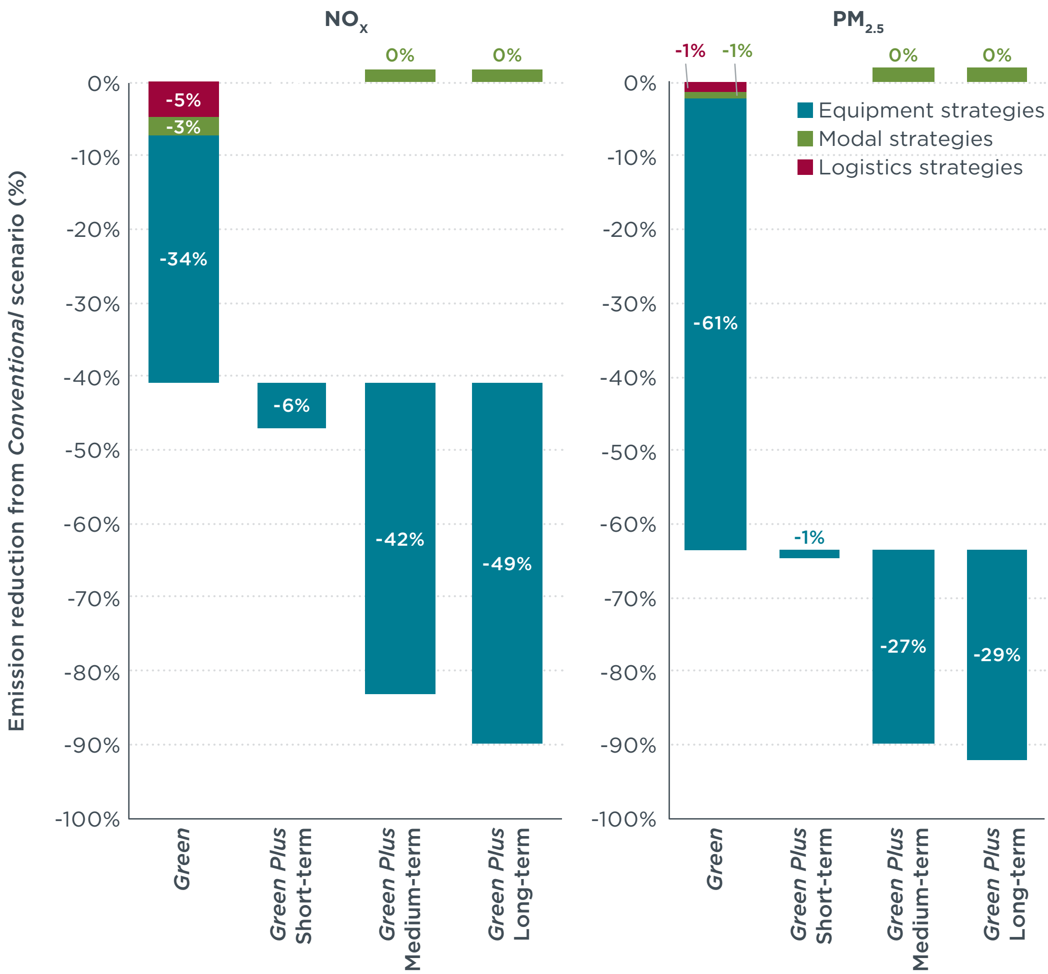


Figure 21. NO_x and $PM_{2.5}$ savings by strategy type for land-based segments

7 The share of health impacts by segment, which is beyond the scope of this study, is not directly correlated with the share of NO_x and $PM_{2.5}$ emissions. The bulk of marine emissions happen over the oceans and away from heavily populated areas, whereas port facilities, highways, and rail yards are in close proximity to urban areas.

CHINA DRAYAGE

This segment covers the transportation of products in China from the factories to the port terminals in Shenzhen—Yantian and Shekou. Because all 11 factories included in the evaluation are within 200 km of the port, drayage trucks are the only mode of transportation employed. Of the 1,778 containers, 88% go directly to the port terminals, and the remaining 12% are consolidated at the CFS near Yantian terminal.

Energy and climate

In the *Conventional* scenario, China drayage accounts for 9% of the supply chain's total energy consumption and CO_2 emissions. Adopted strategies in the *Green* scenario reduced energy and CO_2 emissions by 25%, with logistics and equipment strategies each delivering roughly half of the savings (see Figure 22). All three of the logistics strategies maximize container utilization. Relative to cube optimization, CFS delivers modest energy and CO_2 reductions. Because THD imports large amounts from China, full containers are loaded at the factories, and this reduces the need to rely on CFS for a significant share of operations. Nonetheless, CFS might produce larger savings for companies that import lower quantities of freight, or companies that ship products less frequently.

In terms of equipment strategies, and specifically truck technology, carriers in the *Green* scenario select trucks with smaller engines that consume less fuel than the average drayage truck in China. This is because of the relatively light payload of shipments—less than 10 tonnes per trip—and it underlines the fuel efficiency gains that come from choosing the appropriate truck for the driving cycle and payload conditions. In addition, eco-driving training and techniques saved an additional 2% of energy use and CO_2 emissions. This result is closely tied to avoiding truck idling during cargo loading at factories.[8]

With respect to future strategies in the *Green Plus* scenario, curbing energy use and CO_2 emissions will require significant penetration of fuel-efficient technologies and zero-emission trucks combined with eco-driving training to leverage the benefits. In the short term, emissions can be reduced an additional 11% by moving to trucks with better engine efficiency, low-rolling resistance tires, automated transmissions, and tare weight reduction, among other technologies.[9] Eco-driving training with robust use of information technologies to monitor performance and provide feedback to drivers is also essential. This is not only to reduce fuel consumption, but also to ensure compliance with air pollution emission standards. Medium- and long-term *Green Plus* scenarios have the potential to decarbonize this segment even further. The long-term scenario achieves a 65% reduction from the *Conventional* scenario.

8 Based on interviews with suppliers in Shenzhen. Loading can take up to two hours.

9 Aerodynamics play a relatively smaller role because most driving occurs at lower speeds within Shenzhen's metro area.

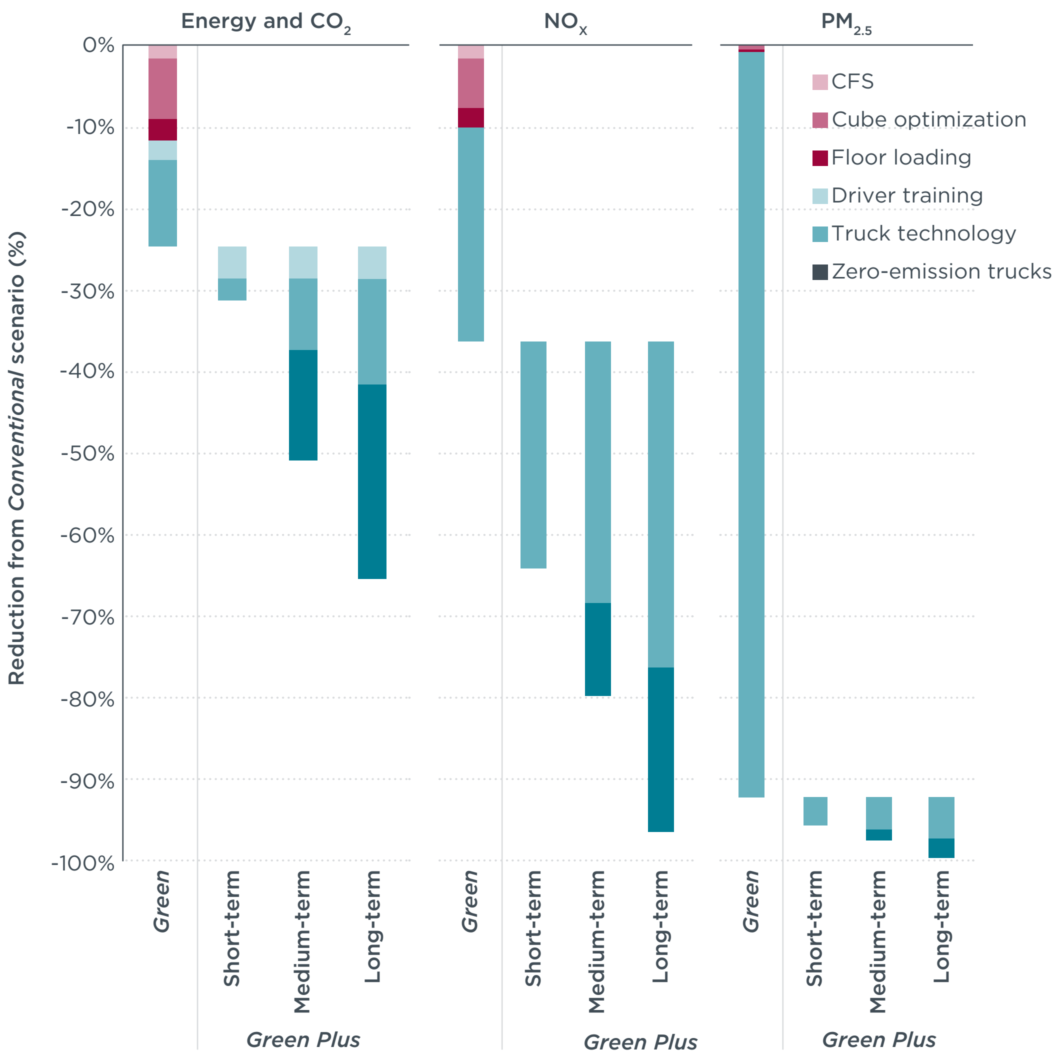


Figure 22. China drayage energy and emission savings by strategy

Health

The bulk of pollutant savings in the *Green* scenario came from the use of trucks meeting China V emission standards, which are estimated to have reduced NO_x emissions 26% and $PM_{2.5}$ by approximately 90% compared with the *Conventional* scenario, under which average truck emission factors are assumed to be close to China III emission levels (Figure 22). Logistics strategies reduced NO_x emissions by an additional 10%, primarily through cube optimization. Logistics strategies had a relatively lower impact on $PM_{2.5}$ reduction in the *Green* scenario because the reductions from the China V emission standards were so high.

As for future strategies in the *Green Plus* scenario, equipping trucks with technologies to meet China VI standards will have a profound impact on NO_x, with savings of 40% when the entire fleet meets this standard in the *Green Plus* long-term scenario. Penetration levels of zero-emission trucks of 10% in the medium term will reduce

NO_x by 11%, and penetration in the long term of 20% will lower NO_x emissions by 20%. Overall, NO_x emissions can be reduced to just 4% of what they are in today's *Conventional* scenario. In the case of $PM_{2.5}$, although significant reductions have already been delivered by China V standards, China VI and zero-emission trucks will be needed to achieve a soot-free trucking sector. The China VI regulation is particularly important because it introduces requirements to ensure that legal emissions limits correspond with real-world savings.

MARINE

Marine is the longest segment in the supply chain and accounts for the largest amount of energy consumption and emissions. THD deploys only container ships in this portion, and thus it is the only ship type analyzed here. The average container ship on this route loads about 10,000 TEUs at the Port of Shenzhen, travels for two weeks at sea, and spends a few hours at the Ports of Los Angeles and Long Beach unloading cargo. This analysis does not consider empty movements associated with return trips from the United States to China.

Energy and climate

In the *Conventional* scenario, the marine segment accounts for 53% of the supply chain's total energy use and CO_2 emissions. Adopted strategies in the *Green* scenario reduced energy consumption and CO_2 emissions by 28%, and the majority of savings came from improvements in vessel technology (Figure 23). Logistics strategies reduce marine fuel consumption by shortening the time at anchorage and at berth. However, the fuel-saving potential of this strategy is limited because ships shut down their main propulsion engines at berth and spend only a small portion of time at those two stages relative to cruising at sea. Indeed, under the *Green* scenario, ships spend less than 10% of voyage time loading and unloading at ports and only 2% waiting at anchorage. The long-term *Green Plus* scenario, with its ambition to zero-out anchorage time and achieve 100% shore power participation at both ports, would yield less than 1% fuel savings combined. That said, these measures would nonetheless reduce air pollution and the related health impacts in port jurisdictions, and this might be particularly beneficial in more densely populated areas.

Modal strategies provide relatively higher fuel savings and emission reductions because they can be employed over the whole voyage. THD commissions some of the largest container ships in the world, but there is still room to improve. The average capacity of container ships in this study is about 10,000 TEUs, whereas the largest container ships in the world can carry more than 18,000 TEUs. Both the origin and destination ports already receive the world's largest container ships, so there is no need for port construction to ensure access. By moving products to larger container ships with no more than an 18% increase in ship length, overall emissions are reduced by 3% in the *Green* scenario and can be reduced by 12% in the long-term *Green Plus* scenario, both compared with the *Conventional* scenario. This would require the shipping industry to deliver more "Triple E-class" container ships, and that is already on the horizon.

Among all the strategies identified to reduce fuel consumption, equipment strategies show the greatest potential. This study considers a wide range of available and next-generation technologies (recall from Figure 15), and one-third of the identified technologies have yet to be adopted by THD. Some technologies such as wind engine, kite assistance, and fuel cell propulsion may take some time to become commercially available. Among the technologies, most are proven to contribute less than 10% to efficiency improvement. One measure, "slow steaming," has already been widely adopted in the container shipping industry and could provide an additional 10%–30% reduction in fuel use. Many of these technologies can be adopted concurrently, with a few exceptions. Fuel cells, for example, are an exclusive engine technology that cannot be combined with most of the other engine-specific improvements. Overall, a combination of these technologies reduces emissions by 25% under the *Green* scenario and reductions of 51% are possible under the long-term *Green Plus* scenario, both compared with the *Conventional* scenario. Combined with other strategy types, energy use and CO_2 emissions in the marine segment can be reduced by 63% under the long-term *Green Plus* scenario.

Health

Logistics, modal, and equipment strategies generate fuel savings, and these also result in emission savings.[10] In addition to fuel savings, emission standards can reduce local pollutants. Marine fuel remains dirty compared with other transportation fuels. The global average marine fuel sulfur content is 25,000 ppm, while on-road gasoline is almost desulfurized and on-road diesel contains only 10–15 ppm. The IMO will enforce a global fuel sulfur limit of 5,000 ppm starting in 2020; this is a leapfrog from the current situation, but still far behind the on-road sector. Fuel savings, together with the sulfur limit, will reduce $PM_{2.5}$ by more than 50% from the *Conventional* to the *Green Plus* scenario (Figure 23). Further actions like an IMO-designated ECA, though smaller in scale, also show clear $PM_{2.5}$ benefits. The enactment of a Chinese ECA as wide as 100 nautical miles would reduce those emissions by 8%–10% of the entire trip. All strategies combined will reduce $PM_{2.5}$ emissions by more than 80% in the long-term *Green Plus* scenario. The continuation of North American ECA implementation would reduce overall NO_x emissions by 6% and a new Chinese ECA would reduce them by an additional 3%. Overall, combined with fuel-efficiency gains, NO_x emissions can be lowered by almost 70% under the long-term *Green Plus* scenario.

10 Fuel savings include savings from logistics, mode, and equipment strategies combined. The breakdown of such savings is the same as that for energy use and CO_2 emissions.

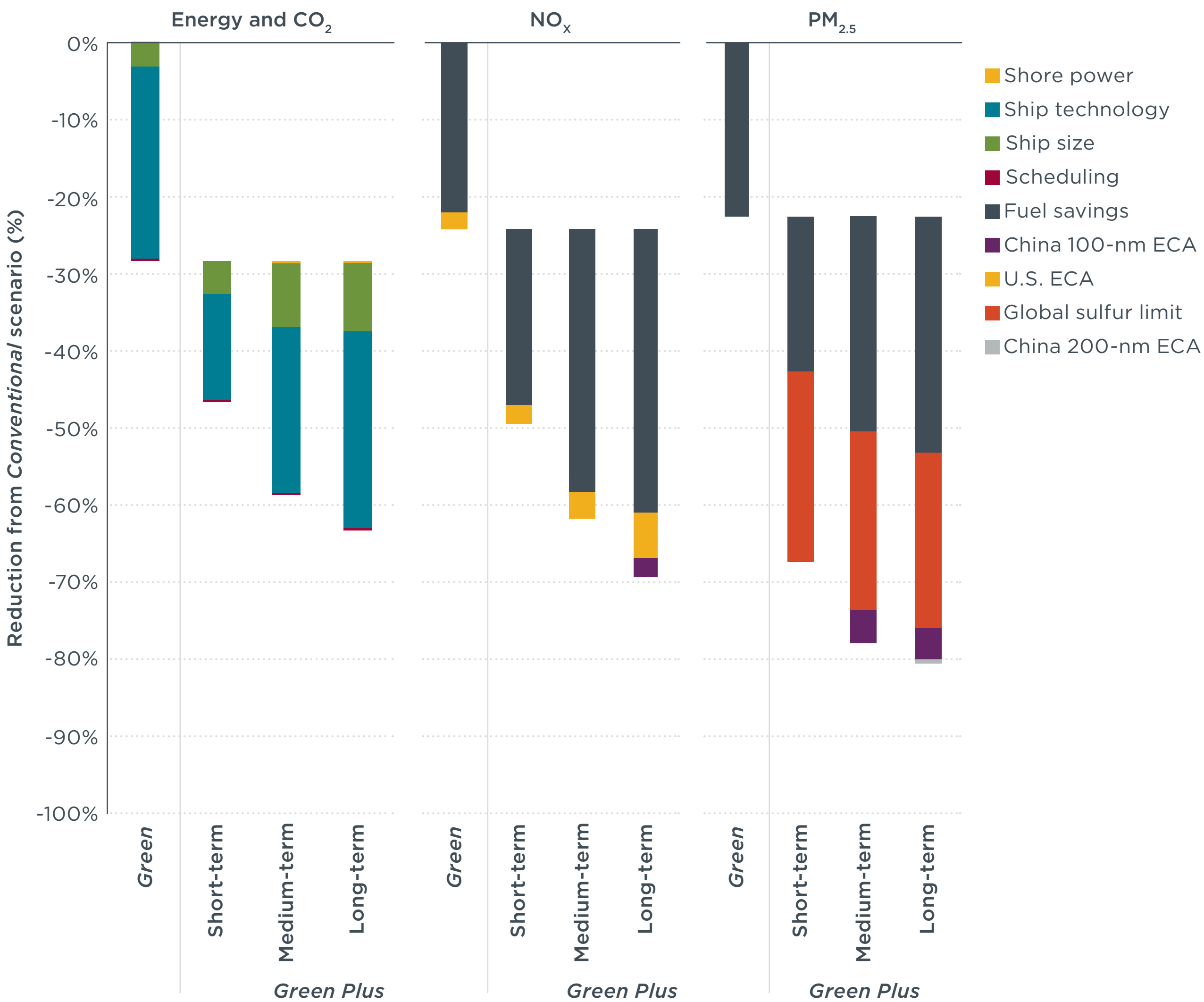


Figure 23. Marine energy and emission savings by strategy

U.S. DRAYAGE

In this segment drayage trucks pick up containers at the Ports of Los Angeles and Long Beach and deliver about two-thirds of them to the TSLD 30 km away. The remaining containers are sent to the closest SDC in Mira Loma 100 km away. This is equivalent to a weighted-average distance of 52 km, making U.S. drayage the shortest segment in the supply chain.

Energy and climate

U.S. drayage accounts for about 6% of the supply chain's total energy use and CO_2 emissions under the *Conventional* scenario. Adopted strategies in the *Green* scenario reduced energy consumption and CO_2 emissions by 35% (Figure 24). Logistics strategies accounted for 25% of the savings, with equipment strategies representing the remaining 10%. Moving containers to the TSLD instead of the more-distant Mira Loma SDC represents the largest contribution of any single strategy. This operation requires network adjustments and adequate inventory planning by THD. Despite the additional stop, the reduction in distance traveled together with cube optimization and floor loading for outbound loads to SDC/RDCs result in significant energy and CO_2 savings. Savings from equipment strategies are primarily due to truck technology from the use of the most efficient SmartWay-registered carriers, which operate relatively more-efficient trucks than the industry average.

With respect to future strategies in the *Green Plus* scenario, curbing energy use and CO_2 emissions will require significant penetration of fuel-efficient truck technologies and zero-emission trucks, alongside eco-driving training to leverage the benefits of these advanced technologies. As marginal improvements in ICE and hybrid technologies decrease in the medium and long term, zero-emission trucks will represent a higher share of savings.

Health

Because U.S. drayage is the shortest segment of the supply chain, it accounts for a relatively small share of local pollutants. However, its emissions intensity is relatively high because older trucks are typically used. In addition, emissions of local pollutants in this segment are likely to have a more pronounced impact on human health because they are released within the Los Angeles metropolitan area, which has approximately 13 million residents. Thus, just as with the China drayage segment, reducing local pollutants here is critical for mitigating the supply chain's health impacts. The assumptions in this segment are aligned with the San Pedro Bay Ports Clean Air Action Plan, enacted by the Ports of Los Angeles and Long Beach in 2006 to significantly reduce air pollution from port-related transportation equipment including ships, trucks, locomotives, cargo handling equipment, and harbor craft ("San Pedro Bay Ports," 2019).

Adopted strategies in the *Green* scenario reduced NO_x emissions by 80% and $PM_{2.5}$ by 93% (Figure 24). The majority of these reductions, in particular for $PM_{2.5}$ emissions, came from truck technology, as THD systematically hires among the cleanest truck carriers under the SmartWay program. Transloading savings are also highly relevant, especially for NO_x emissions, with savings of 16%.

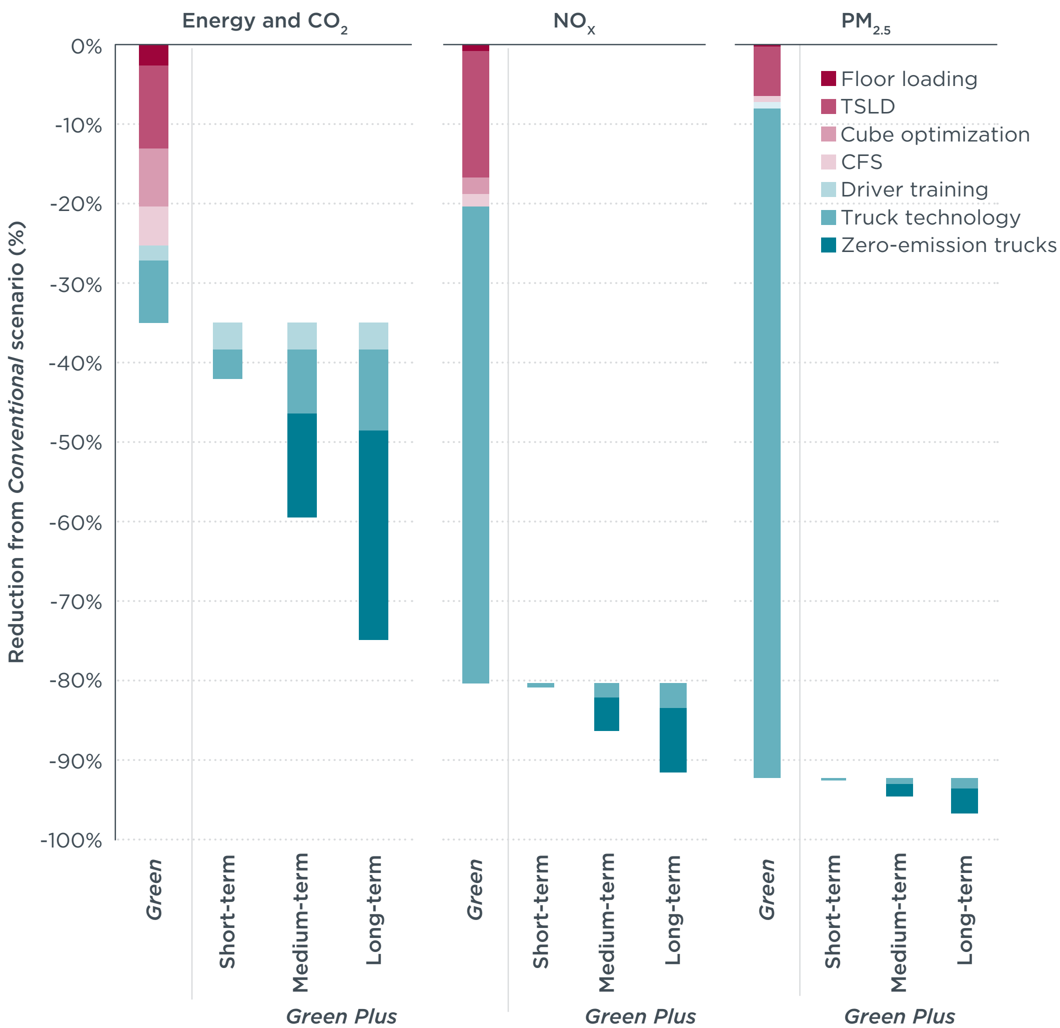


Figure 24. U.S. drayage energy and emission savings by strategy

Although adopted strategies have already reduced local pollutants substantially, finishing the transition to the cleanest trucks (EPA 2010 standard) will save an additional 3% of NO_x emissions and 1% of $PM_{2.5}$ emissions in the *Green Plus* long-term scenario. Since some penetration of zero-emission trucks is expected in the drayage sector, U.S. drayage trucks will reduce NO_x emissions by an additional 8% and $PM_{2.5}$ by an additional 3% in the *Green Plus* long-term scenario, assuming 20% of trips by zero-emission trucks. Altogether, long-term emissions of NO_x will be reduced by 91%, and $PM_{2.5}$ by 97% from the *Conventional* scenario.

U.S. INLAND

This is the longest land-based segment in the supply chain. Freight moves from the TSLD facility to four SDCs and seven RDCs. The weight-adjusted average distance traveled is 1,350 km. This is the only segment with rail operations, given the relatively long distances, and that explains why it is the most efficient land-based segment in terms of energy per tonne-km and the cleanest land-based segment in terms of emissions per tonne-km (recall from Figure 16 and Figure 17). Freight tonnage is split roughly evenly between trucks and rail, but rail accounts for more than 90% of freight activity in tonne-km, given the much longer distances.[11] This explains the significant energy and CO_2 savings from mode shift, as well as the importance of advancing to the cleanest technologies for locomotives.

Energy and climate

U.S. inland accounts for 13% of the supply chain's total energy use and CO_2 emissions, based on the *Conventional* scenario. Adopted strategies in the *Green* scenario reduced energy consumption and CO_2 emissions by 22% (Figure 25). Logistics strategies resulted in significant energy and CO_2 savings. Most importantly, transloading from 40-foot-high cube containers to 53-foot trailers and rail boxes reduced energy use and CO_2 emissions by 13%. Savings from equipment strategies are relatively smaller than those from logistics strategies and come primarily from the use of the most efficient SmartWay carriers.

Because of the improvements already implemented in the *Green* scenario, the incremental savings in the immediate *Green Plus* scenario are relatively smaller and primarily from more-efficient trucks and eco-driving. Shifting freight to rail along medium-distance routes in the medium- and long-term scenarios will result in the largest savings from all strategies. Further reductions in energy use and CO_2 emissions in the medium- and long-term scenarios will require more fuel-efficient trucks and locomotives. This study does not consider zero-emission trucks in this segment because of the long distances, although some zero-emission technologies, particularly fuel cells, are being planned in the long run. As discussed in the following section, cleaner rail technologies are even more critical to reducing air pollution, particularly around densely populated areas.

11 Weight-adjusted average distance is 240 km for trucks and 2,428 km for rail (see Table 4 in Chapter 3).

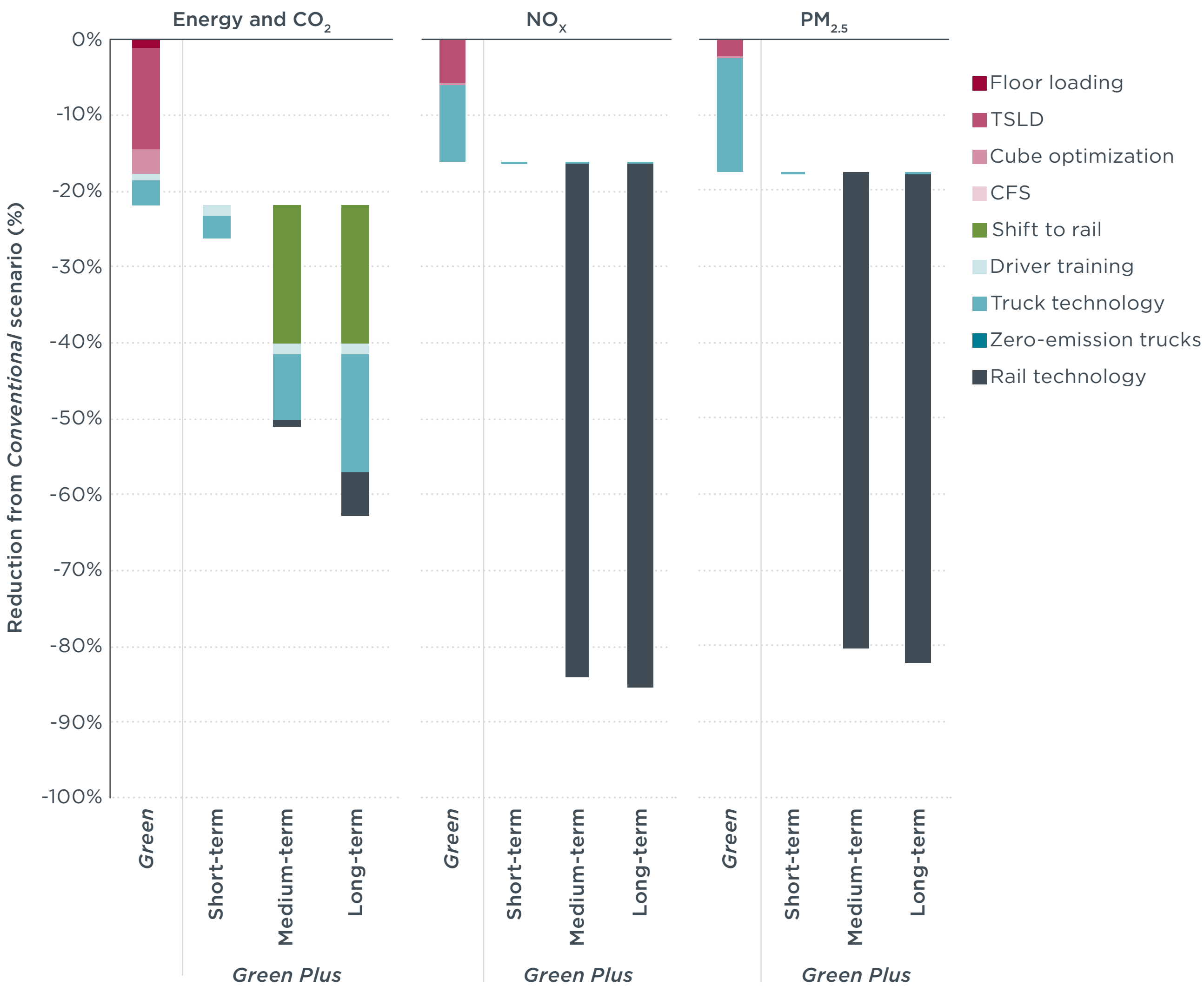


Figure 25. U.S. inland energy and emission savings by strategy

Health

Emissions of local pollutants along this segment are strongly influenced by rail operations. Adopted strategies in the *Green* scenario reduced local pollutants by 16%–18% (Figure 25). The switch to 53-foot trailers had a sizable role in the reduction of NO_x emissions. Truck technology also delivered a significant share of reductions, even though just 10% of freight activity is moved by trucks along this segment. That underscores the importance of the transition toward the cleanest truck emission control technologies.

For future strategies in the *Green Plus* scenario, savings are dominated by improvements in rail technology. This is because truck technology has already advanced considerably in the *Green* scenario and this study assumes no zero-emission trucks for long-distance movements. Savings from rail technology relate to the adoption of U.S. Tier 4 standards for locomotives, which will reduce local pollutants by 65%–70% from the *Conventional* scenario. The medium-term scenario also assumes the use of zero-emission locomotives for 10% of total rail kilometers traveled, and the long-term scenario assumes 20%. Although this strategy has marginal impacts on total emissions, zero-emission locomotives are assumed to be used to densely populated metropolitan areas where human exposure is higher. Mode shift to rail does not result in pollutant savings because of relative advances in truck emissions controls.

SDC TO STORE

Final delivery from the four SDCs to more than 600 THD stores totals almost 10,000 tonnes of products; this is almost 80% of the total freight activity from SDCs and RDCs to stores. The weight-adjusted average travel distance is 300 km, with the most freight—6,924 tonnes—moving from the Mira Loma SDC.

Energy and climate

This segment accounts for 16% of the supply chain's total energy use and CO_2 emissions, based on the *Conventional* scenario. Adopted strategies in the *Green* scenario reduced energy consumption and CO_2 emissions by 23%, with savings equally divided between logistics and equipment strategies (Figure 26). Logistics strategies include better use of truck capacity through cube optimization and floor loading, including the use of full truckloads achieved through more efficient route planning. Equipment strategies include the use of the most efficient SmartWay carriers, which employ a combination of truck technology, operational improvements, and eco-driving training to improve fleet efficiency.

To further reduce energy consumption and CO_2 emissions along this segment, advanced fuel-efficient and zero-emission trucks will be required. In the short term, a higher penetration of fuel-efficiency technologies can save 8% of energy use and CO_2 emissions. In addition, a more systematized eco-driving training program, with adequate data collection, performance tracking, and incentives, can save an additional 4%. While constant improvement of ICE technologies can further reduce energy consumption and CO_2 emissions by as much as 21% in the medium-term scenario and 31% long-term, decarbonization along this segment will also require zero-emission trucks. These can reduce energy use and CO_2 emissions by 10% in the medium term on routes of less than 200 km and 20% in the long term on routes of less than 400 km.

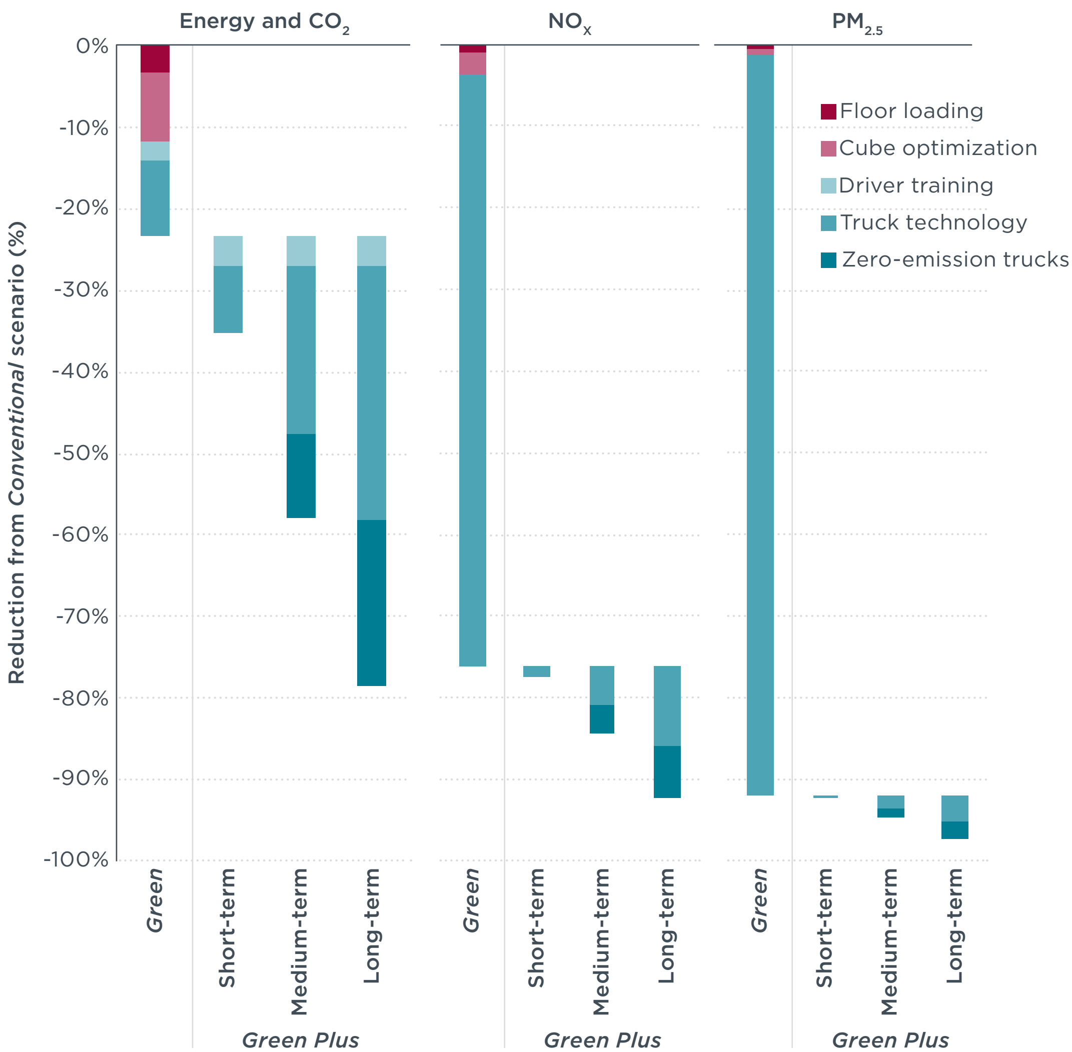


Figure 26. SDC to store energy and emission savings by strategy

Health

Improvements in truck technology have driven and will continue to drive reductions of local pollutants along this segment. Adopted strategies in the *Green* scenario lowered local pollutants by 76%–92% depending on the pollutant (Figure 26), mostly as a result of hiring the cleanest SmartWay carriers. The latest truck emission control technologies can reduce emission rates significantly, making savings from logistics strategies more modest in comparison.

The improvement toward a full fleet compliant with EPA 2010 emission standards together with a small penetration of zero-emission trucks will result in further savings in future scenarios. Altogether, long-term emissions can be 92% lower for NO_x and 97% lower for $PM_{2.5}$. Emission savings from zero-emission trucks are relatively smaller than energy savings because the most advanced ICE trucks already have very low emission rates for the pollutants evaluated in this study.

RDC TO STORE

Final delivery from seven RDCs to more than 600 THD stores totals 3,554 tonnes of products. This is just over 20% of the freight activity from SDCs and RDCs to stores. The weight-adjusted average travel distance is 224 km, with a more balanced distribution of outbound freight across RDCs. This is by design. RDCs, which do not hold inventory, serve as cross-docking facilities where inbound cargo is combined into full truckloads for multistore delivery. This enables a more balanced flow out of RDCs.

Energy and climate

Because of the relatively shorter distances and less freight activity, this segment accounts for 3% of the supply chain's total energy consumption and CO_2 emissions, based on the *Conventional* scenario. Adopted strategies in the *Green* scenario reduced energy use and CO_2 emissions by 24% (Figure 27). The strategies evaluated in this segment and their results on energy usage and emissions are similar to those evaluated in the SDC-to-store segment. One key difference is that the savings from zero-emission trucks are relatively larger because the RDC network has shorter distances to stores. That means that a higher share of zero-emission trucks are used in medium- and long-term scenarios.

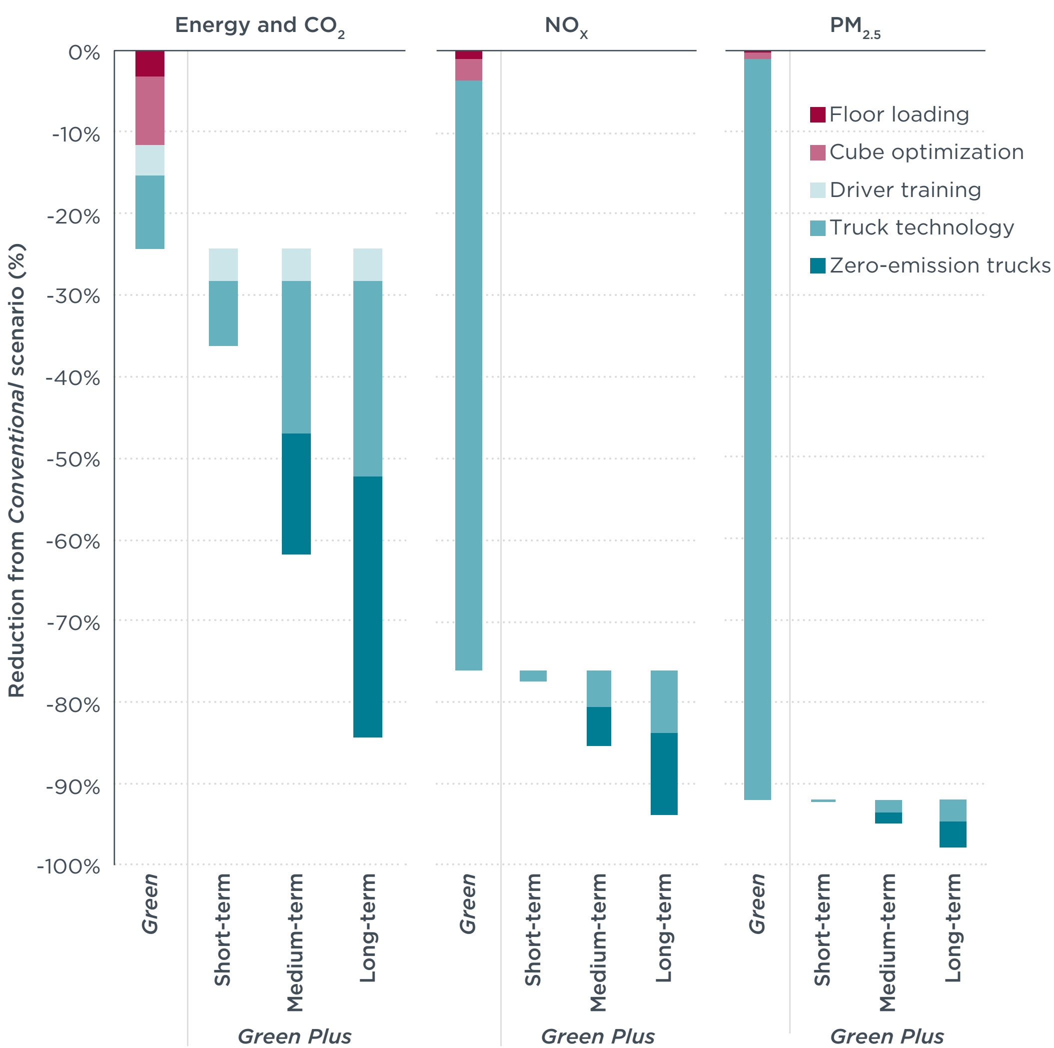


Figure 27. RDC to store energy and emission savings by strategy

Health

Similar to the SDC to store segment, improvements in truck technology continue to result in the majority of savings in local pollutants along this segment. Adopted strategies in the *Green* scenario reduced local pollutants by 77%–92%, depending on the pollutant (Figure 27). In the long-term scenario, emissions are 94% lower for NO_x and 98% lower for $PM_{2.5}$.

CHAPTER 6. **EVALUATION OF POLICIES AND INITIATIVES**

This chapter examines the drivers, barriers, and opportunities for further adoption of energy and emissions reduction strategies. It links them to various market forces, environmental trends, governmental policies, and industry initiatives, and provides insights regarding how industry leaders' actions can be scaled up to the rest of the market through industry benchmarking, reporting and disclosure, sharing of best practices, incentives, and recognition. Finally, this chapter includes preliminary and qualitative considerations regarding the economic case for greener supply chains.

DRIVERS, BARRIERS, AND OPPORTUNITIES FOR STRATEGY ADOPTION

The freight marketplace has evolved considerably in recent years. Changes in demographics, consumer expectations, the penetration of mobile and connected devices, and the rapid growth of e-commerce have each pressured supply chains to deliver products faster while remaining cost-competitive. This can be a challenge because greater supply chain flexibility often results in lower transportation equipment utilization and higher costs. That is, unless adequate planning is in place. Moreover, the trend toward globalized supply chains continues to leverage labor cost savings and lower transportation rates, which do not account for environmental externalities.

Business and industry are also coming to terms with key environmental trends. Deteriorating urban air quality, in particular adjacent to freight facilities, and increasing pressure for climate change mitigation have led more consumers to demand enhanced environmental stewardship and more transparent and committed corporate social responsibility. This has led companies to go beyond business-as-usual practices to take a more proactive stance toward tracking, reporting, and reducing their environmental footprint.

As framed in this study, greener supply chains rely on a combination of clean and efficient logistics, and modal and equipment strategies. Table 15 summarizes government and industry roles in driving the implementation of these strategies. Logistics strategies are primarily driven by industry. This study evaluated the actions taken by THD to date, but it was difficult to estimate the impact of future logistics strategies because they depend on individual shipper decisions. Modal strategies are driven by infrastructure availability, and industry decisions are based mostly on cost, reliability, and lead time. Future mode shift strategies can be estimated, but their evaluation is complex because it depends on a combination of future supply chain configuration, infrastructure investments, congestion and fuel pricing, and the proliferation of distributed delivery. Government policies have a stronger role in equipment strategies because technology-forcing standards and other regulations affect air quality and land use, among other things. In this study, the role of equipment strategies in future supply chains was more prominent because these are more predictable, given technology trends and the known role of government policies in pushing them to the marketplace. The next sections describe government and industry roles, barriers, and opportunities to advance these three strategy types.

Table 15. Drivers for strategy and policy adoption

		Government and industry roles[a]	Logistics	Modes	Equipment
Government role	Regulations	Air quality standards			●
		Fuel quality standards and low-carbon fuel mandates			●
		New equipment efficiency and emissions regulations			●
		Fleet renewal schemes[b]			●
		Truck size and weight regulations	●		
		Low-emission zones and emissions control areas			●
		Freight land-use regulations	●		
		Time and place restrictions on freight equipment	●		
		Research and development	●	●	●
	Market mechanisms	Green freight programs[c]	●	●	●
		Infrastructure investments		●	
	Fiscal instruments	Fuel and vehicle taxation	●	●	●
		Congestion pricing	●	●	●
		Grants for new technologies			●
Industry role		Cargo consolidation	●		
		Network optimization	●	●	
		Load optimization	●		
		Route planning	●		
		Load matching	●		
		Selection of more efficient modes		●	
		Prioritizing clean and efficient carriers			●
		Managing driver performance			●
		Carbon/emissions accounting and reporting	●	●	●

a. Civil society has an important role to play in supporting both government and industry in research and implementation of these strategies and policies.
b. This could also be classified under Fiscal instruments.
c. This could also be classified under Industry role.

Logistics strategies

Shippers, 3PLs, and carriers are the key decision makers in implementing logistics strategies. Shippers, either directly or indirectly through 3PLs and freight forwarders, can optimize their logistics network and consolidate cargo to improve equipment utilization and reduce the number of trips. This can be accomplished through the use of consolidation facilities, higher-capacity equipment, and multistop pick-ups or deliveries. Large shippers can skip the use of consolidation facilities by consolidating cargo at origin. This is similar to what THD does in China, where only a small share of shipments travel through the CFS. Small shippers can collaborate by sharing warehousing and transportation equipment. Shippers can also increase equipment utilization by building loads that optimize transportation equipment capacity. For example, THD has implemented cube optimization and floor loading to maximize container and truck utilization. Carriers can optimize distance traveled by improving multistop routes and reducing empty mileage. Some carriers have already started investing in the entire supply chain to optimize intermodal operations and reduce future risks should market conditions fluctuate.

Government can influence logistics operations indirectly. First, fuel and vehicle taxation and congestion pricing can better internalize environmental externalities, thus encouraging more efficient use of transportation equipment and fuels. Second, government can change truck size and weight regulations to allow for more productive trucks while considering their effects on infrastructure and public safety. Third, government can implement land-use regulations that influence the development of freight facilities in ways that improve logistics operations. Lastly, government can limit access to freight vehicles based on time and place. Many urban areas impose limitations on night deliveries, as well as access to some roads at the urban core. In the case of China, the government restricts coal movements with trucks in northern ports like Tianjin and Tangshan.

Reducing empty mileage is a major challenge in pursuing better logistics efficiency. Increasing equipment utilization leverages capacity and makes better use of assets, which can reduce capital costs if fewer assets are needed to move the same amount of cargo. Barriers to reducing empty mileage include imbalances in trade flows, lack of visibility of truck capacity, and lack of collaboration across shippers and carriers. Other important barriers are freight capacity limitations and congestion; the congestion happens in ports and other major freight facilities, and along heavy freight highway corridors, especially during peak times. Related to congestion are off-peak limitations from hours-of-service regulations and loading dock restrictions on hours. There are also economic barriers to freight consolidation, as it can result in additional lead time and facility costs. Finally, there are barriers to the use of floor loading because it increases loading and unloading times and the risk of cargo damage. This is why palletized cargo is the industry standard.

With respect to opportunities for improving logistics efficiency, bilateral partnerships (Mathers, Wolfe, Norsworthy, & Craft, 2014) and information-sharing platforms for load matching could increase collaboration across industry partners and help fill transportation equipment. Off-peak incentives help alleviate congestion and save costs from lower road and bridge tolls, less fuel consumption, and more expedient lead times (Browning et al., 2017). The localization of supply chains could also help reduce empty mileage by removing marine segments where trade imbalances are most prominent. In addition to near-shoring of suppliers, companies can consider 3-D printing options to replace components and parts that would otherwise be shipped over long distances.

Modal strategies

One of the main barriers to more mode shifting to rail and waterways is that trucking is better positioned to fulfill the demand for smaller, just-in-time e-commerce shipments. Second, in most markets there are limited public funds for rail and waterway infrastructure. Third, fundamental technology advances in trucking have substantially improved energy efficiency and emissions, diminishing the relative advantages of rail and waterways. Advances in autonomous trucks will only add to this trend, as trucking costs are further reduced. Fourth, rail innovation is slower than other modes because it passes through more regulated environments and rail assets have long lifetimes. Finally, railyards and ports typically contribute significantly to local air and noise pollution, and often generate strong opposition from local groups in the absence of mitigation measures.

Government can help overcome these barriers and drive shifts to more energy-efficient and environmentally friendly modes. Most directly, government can invest in rail and waterway corridors, as infrastructure availability is one of the main drivers of growth. Infrastructure investment can vary greatly by country. In the United States, for example, the freight rail system is privately owned and operated and thus cannot use the Highway Trust Fund. The U.S. inland waterway system, however, is funded by the Inland Waterways Trust Fund and the federal General Fund. The Inland Waterways Trust Fund has been so heavily drawn that it does not have sufficient funds to fulfill lock and dam maintenance and modernization needs (Cambridge Systematics, 2013). In China, with the rapid development of foreign trade and the highway system, the inland waterway system is much less used. Given the abundant inland waterway capacity, the government is now more and more inclined to promote modal shift to these systems, especially to better connect with international shipping routes. However, achieving that requires public funding to not only improve infrastructure, but also provide economic incentives for supply chain enhancement.

Second, government can further deregulate the freight rail market, particularly in China. Deregulation of rail markets has shown that operators can reduce costs effectively. For example, in the United Kingdom, staff productivity has improved by roughly 60% in a decade, while the number of locomotives has been cut in half despite increased rail traffic (Girardet, Müller, & Ott, 2014). Third, government can level the playing field by harmonizing rail infrastructure and signaling systems, by increasing train lengths, and by harmonizing trucking standards and hours of service regulations in regions lacking harmonization. Finally, government can expand the use of direct user fees for freight and establish GHG pricing mechanisms, which would reduce the environmental externalities from freight transportation.

Industry can have a direct role in the expansion of freight rail and waterway corridors. First, industry can improve staff and asset productivity to improve their competitiveness in increasingly deregulated markets. Second, industry can invest in data solutions to reduce costs and provide customers with a more seamless experience (Girardet et al., 2014). Operators can use data to more accurately predict demand and manage pricing, capacity, and schedules. Data can also provide a more transparent experience for customers via integrated booking systems and systems for shipment tracking. Train-flow planning software can reduce unnecessary braking and stopping and consequently reduce fuel use. Predictive maintenance powered by sensors can reduce rail stock and infrastructure downtime and lower costs. Data solutions can also be used to reduce personnel shift changes and delays.

Third, industry can improve schedules to provide more reliability and attract new traffic. Rail and waterways have reliability advantages from not being subject to road traffic patterns, conditions, and congestion, especially in markets where they do not share infrastructure with passenger traffic. Scheduling improvements can leverage this advantage and lead to both better asset utilization and better positioning to serve a just-in-time inventory market. Finally, industry can form coalitions to promote the use of more-efficient equipment without necessarily moving to a different mode of transport. For example, the Clean Cargo Working Group is a group of leading maritime carriers and shippers that collaborate to improve the energy-efficiency of container shipping generally and across specific routes.

Equipment strategies

Government should have a comprehensive policy portfolio to improve the energy efficiency and environmental performance of freight equipment. First, government can implement regulations. Ambient air-quality standards, low-emission zones, and ECAs for marine vessels are policies that limit the use of the dirtiest equipment. Technology-forcing regulations more directly influence the energy and environmental performance of new transportation equipment. Major vehicle markets such as Japan, China, the United States, India, and the European Union have set fuel consumption or CO_2 targets for HDVs. All major vehicle markets have already adopted Euro VI-equivalent HDV emissions standards, the cleanest to date, and post Euro VI/U.S. 2010 policy development has already started in the United States and Europe. The United States has also implemented its stringent Tier 4 standard for locomotives that entered production in 2015. These standards, however, can be further tightened to achieve even more emissions reductions. Fuel quality and low-carbon fuel mandates could also lead to better sustainability of diesel and marine bunker fuel if they properly account for the life-cycle carbon intensity of biofuels. Assessing the long-term availability of low-carbon biomass fuels for international shipping is beyond the scope of this work. Recent studies (Lloyd's Register, 2019) have highlighted sustainable biomass as one possible pathway to decarbonizing international shipping, but further work is needed to assess the competitiveness of these fuels compared with alternatives such as renewable hydrogen or ammonia.

The bellwether of policies relevant to the marine segment is the IMO. Marine emission reductions rely heavily on IMO efforts, as the majority of this segment is on the open sea. On air pollution, the IMO has been steadily lowering the global sulfur limit over time. Starting in 2020, this limit will be lowered to 5,000 ppm from the current average of 35,000 ppm; though a significant step, this is still high compared with equivalent fuel-quality standards for on-road vehicles of 10-15 ppm for diesel fuel. IMO Member states have the ability to impose more-stringent air pollution regulations around sensitive regions such as coastlines and for domestic ships and engines. The IMO finalized its initial GHG strategy in 2018 (Rutherford & Comer, 2018), including a long-term decarbonization goal and a list of potential short-, mid-, and long-term measures to support that goal. Industry's voluntary efforts in modal shift, increased efficiency, and logistics strategies can all support the IMO's efforts. Individual governments can work to establish national action plans to invest in, support, or remove barriers to these strategies.

Second, government can introduce fiscal mechanisms to encourage cleaner fleets. Fuel and vehicle taxes are known to have a direct effect on vehicle fuel efficiency performance (He & Bandivadekar, 2011). Government financial assistance under vehicle replacement programs seeks to replace older and gross-emitting vehicles with more efficient and cleaner vehicles (Posada, Wagner, Bansal, & Fernandez, 2015). The U.S. Diesel Emissions Reduction Act (2007-2016) and related state energy and air-quality programs have enabled many businesses, through loans and grants, to retrofit and replace older, less efficient, more-polluting freight equipment and vehicles with newer, greener options. Financial incentives can also promote shore power adoption for ships at berth, which can greatly reduce the acute health impacts of ship-induced air pollution in populated port cities. Governments also support international development banks and other global programs that offer fiscal incentives.

Third, government can introduce green freight programs, which provide access to financing mechanisms and information about fuel-saving technologies, strategies, and fleet performance so that trucking fleets and shippers can make informed decisions that save fuel and lower costs (Sharpe, 2017). These green freight programs can be expanded to include shipping, especially in inland waterways or domestic coastal shipping lanes where advanced low-emission or even zero-emission technologies can be demonstrated.

Industry also has an important role in accelerating technology advancement to improve fleets' energy and environmental performance. Carriers can use real-world efficiency data to improve truck efficiency and driver performance. By understanding how different technologies and driver behavior affect truck efficiency, they are better equipped to purchase more fuel-efficient equipment and introduce programs for better driver performance. Shippers and 3PLs can prioritize hiring more energy-efficient carriers, thus leveraging market mechanisms that drive better fleet performance. By using SmartWay data, THD not only prioritizes hiring the most efficient carriers, but also rewards more-efficient carriers with premium rates. Ports can also provide incentives for cleaner fleets, such as the ability to use shore power at berth for those with the most advanced Tier III engines. Some ports also reduce port drayage fees for cleaner trucks. For example, the Ports of Los Angeles and Long Beach will exempt zero-emission trucks from port fees starting in 2020.

Many barriers prevent faster efficiency improvements in transportation equipment. Because of low barriers to entry, trucking is a highly disaggregated sector in which most carriers have just a few trucks or are owner-operators. Fierce competition depresses profits and prevents investment in more-efficient trucks without financial assistance. Since these trucking companies own only the trucks, which depreciate rapidly, most lack access to capital and loans for investment. There are also split economic incentives for some carriers, meaning that the gains from better efficiency do not stay with those who own the equipment, thus discouraging investment. Information barriers about the real-world performance of advanced technologies delay investment decisions and deter carriers from pressuring vehicle makers to incorporate new technologies faster. In addition, advanced powertrain technologies, such as hybrid and electric-drive trucks, and recharging infrastructure are not yet mature enough for widespread adoption (Browning et al., 2017). Because transportation equipment also has a very long lifetime and typically lingers in the fleet for decades, this delays the benefits of new technologies. This is especially true for ships, which usually have a life span of 25 to 30 years. Finally, fuel prices do not properly account for environmental externalities from fuel combustion, and this limits the incentive to invest in better efficiency and environmental performance.

There are many opportunities, however, to overcome such barriers. Vehicle taxation targeting the least efficient and dirtiest vehicles can result in important energy and emissions savings. Fleet renewal schemes can replace the dirtiest and oldest vehicles with newer and cleaner equipment. For ships, government can start scrapping smaller and often dirtier vessels in the inland waterway system and retire the old fleet by implementing a vessel standardization program. Improved data collection and management through telematics and other data monitoring and reporting systems can provide better information about which technologies and driver behaviors result in improved fleet performance. Government can also provide additional incentives for fleet electrification, including super credits under HDV fuel-efficiency regulations, charging infrastructure programs, and local policies such as allowing nighttime electric urban delivery vehicles. On the path toward transportation electrification, air-quality concerns, equipment duty cycles, and recharging infrastructure availability are likely to drive the adoption of applications such as port cargo handling equipment.

INDUSTRY BENCHMARKING AND REPORTING

The variety of strategies considered in this study underscore how virtually any industry player, at any performance level, can adopt environmental strategies, where relevant, that are similar to those already taken by industry leaders. The gap between the *Conventional* and *Green* scenarios represents an achievable performance enhancement between industry benchmarking and industry average practices. Based on the findings of this study, significant savings—on the order of 30% for energy use and CO_2 emissions, and 23%–25% for local pollutants—can be achieved by adopting current best practices. For strictly land-based supply chains, savings of local pollutants ranging from 34%–61% can be achieved today by prioritizing procurement of the cleanest and most efficient truck carriers available.

This study is limited in that it relies on a single data point. This prevents the generalization of conclusions to the rest of the market. First, the supply chain evaluated is unique; while the China to the U.S. trade corridor is a common one, the supply chain analyzed is certainly not representative of an industry average. Additionally, this study relies on very detailed industry data and operational insights to determine energy and emissions savings. However, it is difficult to compare these practices with those from other industry sectors. In addition, industry data are rarely public, and this makes it hard to determine how other companies in other industries might compare. Based on SmartWay data, THD is rated as a "High-Performer" shipper (EPA, 2017a), but there is no public data on the relative rankings of high- and non-high performers because of data confidentiality.

Despite these limitations, SmartWay carrier performance data provide insights about relative efficiency (Figure 28). SmartWay carriers are divided into and compared within peer groups based on operation and equipment type. Carriers fall into one of five performance ranges for each of SmartWay's six performance metrics: grams per mile and grams per tonne-mile for CO_2, NO_x, and PM. Values in the figure are based on CO_2 per tonne-mile. SmartWay carriers can see how they compare with SmartWay peers and decide to improve performance. Since SmartWay carriers are expected to perform better than non-SmartWay carriers, there is significant potential for energy and emission savings by selecting high-performing carriers.

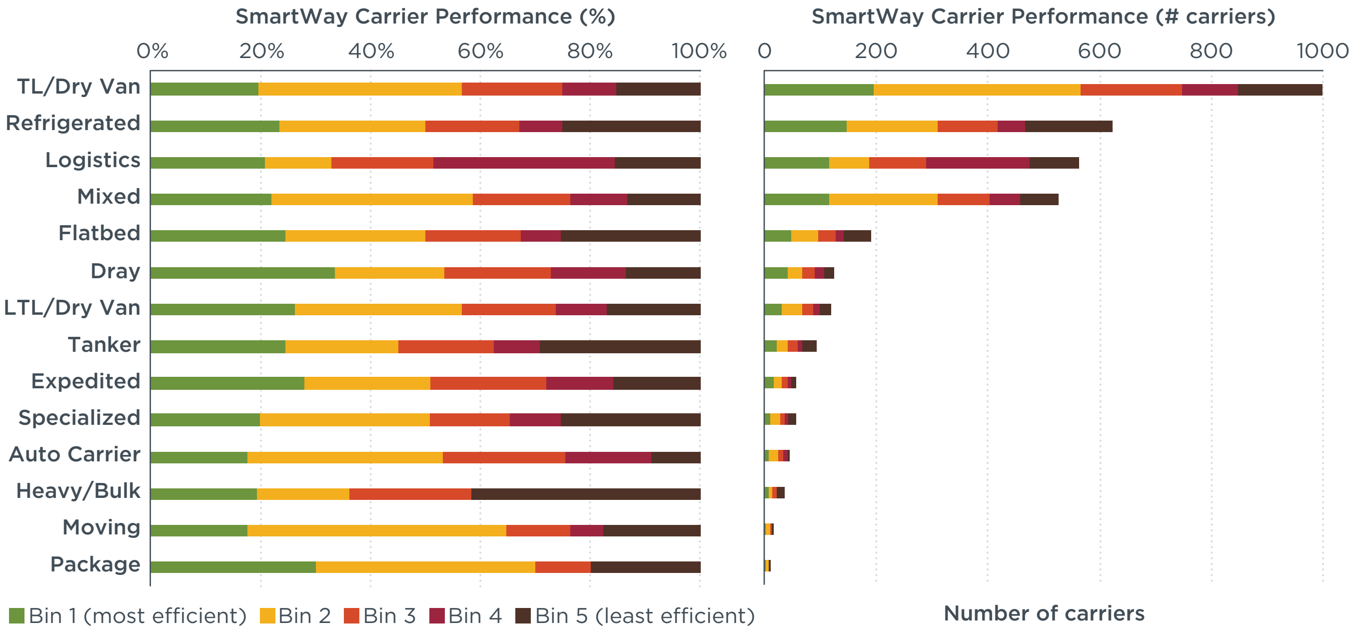


Figure 28. SmartWay carrier performance data (EPA, 2017a)

Good data and reporting are critical in assessing the potential of strategies and tracking the improvements after implementation. Furthermore, a company's credibility on green equipment and logistics is dependent upon transparent reporting on GHG and air pollutant emissions to customers and the wider public. The GLEC Framework provides a universal methodology for calculating and reporting GHG emissions across multimodal supply chains. Advanced methods for data collection and management such as electronic data loggers can also provide better information about which technologies and driver behaviors result in better fleet performance.

ECONOMIC CASE FOR GREENER SUPPLY CHAINS

A country with efficient freight systems has the potential to be more competitive than less efficient peers in terms of trade. The benefits of this could include more resources available for socially and economically beneficial programs. Freight accounts for about 7.5% of U.S. GDP (U.S. Department of Commerce, 2016), and 14.6% of Chinese GDP (Fung Business Intelligence, 2017). The World Bank also publishes its Logistics Performance Index, which considers parameters such as customs efficiency, infrastructure, ease of arranging competitively priced shipments, quality of logistics services, ability to track and trace shipments, and timeliness of shipments. Currently the United States ranks 14th and China ranks 26th among the 160 countries evaluated (World Bank, 2018).

In lieu of a comprehensive cost-benefit assessment of the strategies evaluated, this study provides qualitative insights on the economic case for greener supply chains. First, it is important to consider energy and CO_2 savings separately from local pollutants. The benefits from reduced energy use and CO_2 emissions include fuel and cost savings realized by companies, but the benefits from cutting local pollutants are in the form of reduced health impacts. The latter are not easily internalized by companies.

While all strategies that reduce fuel consumption result in direct fuel-related cost savings, fuel costs are just one part of transportation expenses. Such expenses also include labor, equipment depreciation, maintenance, and insurance, among others. Figure 29 provides a 2017 breakdown of operational trucking costs in the United States, and it illustrates how fuel represents, on average, 22% of trucking costs. This is second only to driver costs. During periods of higher energy costs, fuel can exceed labor as the greatest cost center in developed and developing countries and regions.

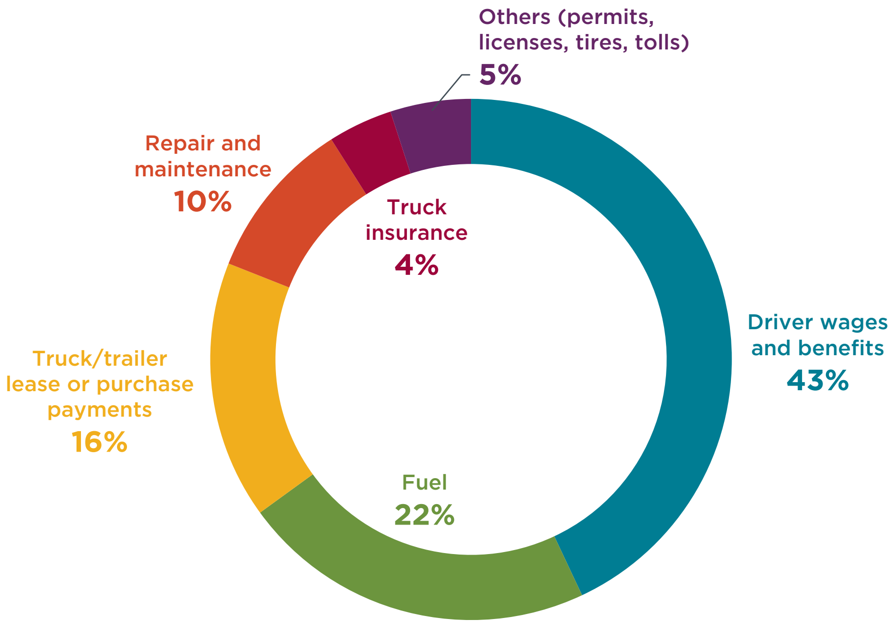


Figure 29. Breakdown of trucking costs in the U.S. in 2017 (American Transportation Research Institute, 2018)

Table 16 summarizes the expected effects of logistics and equipment strategies on trucking costs. Because modal strategies will shift freight away from trucking, it is assumed that overall costs will decrease because rates for other modes are typically cheaper than trucking rates on a tonne-kilometer basis.[12] In addition to fuel savings, logistics strategies will also reduce costs associated with distance traveled such as driver wages, insurance, and maintenance. In the case of equipment strategies, more advanced and expensive equipment could increase equipment depreciation, insurance, and possibly maintenance. However, labor costs, which represent the highest cost category, are not expected to increase because of more advanced and efficient trucks.

12 This assumption typically does not apply to short-distance trips where rail is not cost-competitive with trucks.

Table 16. Expected effects of logistics and equipment strategies on trucking costs in the U.S.

<table>
<tr><th>Cost category</th><th>Logistics strategies</th><th>Equipment strategies</th></tr>
<tr><td>Fuel</td><td>↓</td><td>↓</td></tr>
<tr><td>Driver wages and benefits</td><td rowspan="3">↓ A reduction in vehicle-kilometers should reduce costs, all else held constant.</td><td>— Although more advanced equipment could require additional training, it is not expected to increase labor costs in substantial ways.</td></tr>
<tr><td>Equipment depreciation</td><td>↑ More advanced and expensive equipment will result in higher equipment depreciation.</td></tr>
<tr><td>Maintenance</td><td>— More advanced equipment could result in higher costs (e.g., urea, DPF maintenance) or lower costs in the case of electric-drive trucks.</td></tr>
<tr><td>Insurance</td><td>↓ Although insurance is often not proportional to distance driven, less vehicle activity can lead to reduced fleet sizes, which would likely result in lower insurance costs.</td><td>↑ Because insurance costs are typically tied to equipment cost, they could increase because of more advanced and expensive equipment. An exception is equipment bringing both fuel and safety benefits (e.g., adaptive cruise control).</td></tr>
</table>

Although the reduction of local pollutants does not deliver direct cost savings to shippers and carriers, it has a critical social impact and significantly reduces costs associated with health impacts (Chambliss et al., 2013). Cost-benefit analyses of Euro VI-equivalent standards for heavy-duty trucks, the cleanest to date, indicate that economic benefits from lower premature mortality outweigh technology costs by a ratio of 8–16 to 1, depending on the country evaluated (Miller & Façanha, 2016). In addition, mitigation of air pollution is a key target of corporate social responsibility efforts from leading companies, which seek to reduce the impacts on disadvantaged communities near ports, warehouses, and highways.

Markets are also increasingly considering a company's environmental, social, and governance track record, and this can directly influence brand and reputation. As a result, companies are highlighting environmental actions and performance in corporate sustainability reports to consumers, investors, and rating companies.

Technologies to green the on-road segment—including truly zero-emission technologies—can potentially be applied to the marine segment. Though doing so requires additional capital and operational investments, as technologies become more mature and are demonstrated in more successful applications, the costs will decrease over time. The cost-effectiveness of reducing local pollutants from ships is particularly good. Past and existing ECA applications have all demonstrated attractive cost-benefit ratios or cost-effectiveness numbers compared with other land-based control measures. For example, the North American ECA application (EPA, 2009) estimated that the program's cost for SO_x reduction through fuel switching would be about $1,200 per tonne and for NO_x reduction about $2,600 per tonne (in 2008 dollars). This could be well below many on-road control policies.

CHAPTER 7. **OUTLOOK FOR FUTURE RESEARCH**

The future research opportunities discussed below are based on the study's limitations. These are related to data and information gaps, the intrinsic uncertainty about future trends, and the need to narrow the scope to the benefits of the most relevant or impactful transportation strategies.

Table 17. Study limitations and outlook for future research

Study limitations	Outlook for future research
Representativeness of the study. Because the study is specific to one shipper and trade route, the strategies and conclusions will not be suitable for all shippers.	Future research can evaluate other major trade routes and other industry sectors, and then highlight differences from this study. Such work would help scale up conclusions toward a roadmap for near zero-emission regional or global freight systems. Subsequent research could also evaluate the effects of globalized versus localized supply chains.
Exclusion of evaluation of local health impacts. Although health impacts are local and directly affect communities adjacent to freight facilities and corridors, this analysis is limited to the quantification of local pollutants.	Health impacts of freight facilities, in particular around major ports and rail yards, are well known and documented. However, future research could provide a more comprehensive assessment of health effects and benefits from the strategies evaluated in this study, to provide a stronger case for faster renewal and electrification of transportation equipment.
Tank-to-wheels emission analysis. This study was limited to tank-to-wheel processes, or fuel combustion.	Future research can incorporate well-to-wheels emissions to provide a more complete assessment of supply chain emissions. This will be especially relevant as the use of electrification and low-carbon biofuels increase in the future.
Limited assessment of future strategies. Because the primary objective of this study is to evaluate a real-world supply chain, it does not conduct a comprehensive evaluation of all future advanced strategies.	Future research could address three topics involving the evaluation of advanced future energy- and emissions-saving strategies: • Potential to improve logistics efficiency by the reduction of empty mileage. Recent research indicates that 15%–25% of U.S. trucks run empty, while the remaining non-empty trailers are just 64% utilized (Mathers et al., 2014). Data on empty mileage in developing countries is difficult to access, but anecdotal evidence indicates that empty mileage can reach as much as 40% or more in some markets. • Potential for and benefits from widespread mode shift to rail, short sea shipping, and inland waterways through the expansion of infrastructure investments, fiscal instruments, and market deregulation. • Evaluation of wide-scale fleet electrification of long-distance transportation for trucks, rail, and shipping.
Exclusion of cost-benefit analysis of strategies.	Although fuel savings are an important driver of energy- and emissions-saving strategies, a more comprehensive cost-benefit analysis could highlight costs and savings not related to fuel consumption, examine why some cost-effective strategies are not being widely adopted, and evaluate fiscal instruments to scale them up.
Production quantities are held constant over time. The study does not address the potential impacts of future network capacity and congestion, both of which can negatively impact energy and emissions because of longer wait times and stop-and-go traffic conditions.	Future research can evaluate how projected infrastructure and equipment constraints can influence the energy consumption and emissions benefits of strategies, thus providing a more accurate assessment. For example, logistics and modal strategies can reduce congestion, and those emissions benefits are not captured in this research. In addition, electrified equipment is more efficient than ICEs in congested conditions, and these benefits are not captured, either.

Finally, this project could be the starting point for an advanced logistics collaboration platform, where industry leaders share and exchange performance data; showcase advanced supply chains; demonstrate results from benchmark technologies, strategies, and pilot projects; and discuss ways that industry and government can collaborate to speed their adoption. While the growth and integration of global supply chains underscores the need for more-comprehensive data and information exchange to foster innovation and efficiency gains, advances in data-collection capabilities and networking will most likely make collaboration more feasible in the near future. Multinational businesses with multimodal and global supply chains are under increasing pressure from shareholders, customers, employees, and other stakeholders to report and reduce their emissions. Finally, more and more countries are moving to implement green freight programs like SmartWay or variants to address policymakers' needs to reduce carbon. Thus, the drivers of more-comprehensive supply chain carbon accounting are aligning with trends that can foster more cooperation on a global scale.

The same types of performance data that were used in this study are essential to decision makers at the enterprise level who are working to optimize supply chain performance and efficiency. Thus, more-complete and better-quality data will further enhance companies' ability to assess operations, optimize mode and carrier selection, and do goal-setting and accurate reporting. However, an organization's ability to do this in a coordinated fashion is limited by the patchwork of existing green freight programs and datasets, as well as gaps where little or no data are available. Furthermore, the various methodologies, metrics, and standards in freight carbon accounting make these efforts even more challenging.

Numerous efforts are underway to streamline and harmonize these efforts globally, including the GLEC Framework (Smart Freight Centre, 2019), the Global Green Freight Action Plan (Climate and Clean Air Coalition, 2015), and even a potential ISO standard (Gasiorowski-Denis, 2015). The EPA and other policymakers are working with business leaders and civil society to expand programs like SmartWay and other freight accounting and reporting in ways that streamline and facilitate standard methods and tools. As a global standard emerges, a global data exchange and collaboration platform would most certainly accelerate efficiency efforts and emissions reductions. Future research could be directed toward how a platform could be developed and implemented in ways that support the shared goals of these key stakeholders.

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APPENDIX A. DATA SOURCES AND EMISSION CALCULATION METHODS

Several methodologies have been developed to guide companies, public entities, and other organizations in calculating the energy consumption and emissions from transportation. This study uses two methodologies to estimate supply chain energy consumption and emissions—one for the land-based links and the other for the marine link. As described below, land-based calculations are based on guidance from the Global Logistics Emissions Council (GLEC) Framework led by the Smart Freight Centre.[13] Marine calculations are based on the ICCT's Systematic Assessment of Vessel Emissions (SAVE) model, which leverages vessel-specific data and provides more specificity than industry average estimates.

LAND-BASED METHODS

These methods apply to all land-based links. Travel distance and fuel efficiency/emission factors are necessary to estimate energy consumption and emissions (Figure A1). The basic logic behind this approach is to define how much (in tonnes) and how far (in kilometers) freight is moved—i.e., freight activity measured in tonne-km—for each vehicle and fuel type based on specific fuel efficiency and emission factors. Given the complexity of obtaining disaggregated data, fuel efficiency and emission factors are used as a proxy for the average vehicle technology and fuel quality used for a specific transportation mode, corridor, or region.[14]

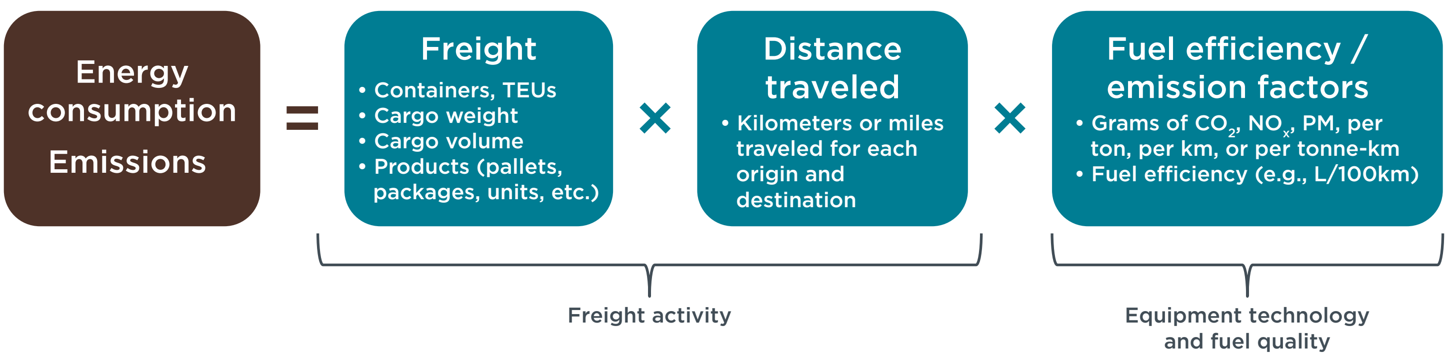

Figure A1. Energy consumption and emissions calculation framework

For this study, THD provided three types of data to calculate supply chain emissions:

» **Freight activity.** THD provided product-level data for all shipments coming from China to the United States for three suppliers in 2017. Disaggregated by individual products in stock keeping units, or SKU, this database contained information on purchase order number, quantity ordered, container ID and size, origin factory, shipment type, ship name, and other information used to estimate freight activity.

13 The GLEC framework is built upon mode and sector specific methodologies already validated by the industry and experts such as the Greenhouse Gas Protocol, the UN's Intergovernmental Panel on Climate Change Guidelines, the International Maritime Organization methodologies, the Clean Cargo Working Group, the U.S. and Canada SmartWay program, and European regulations.

14 See Annex 5 of the GLEC Framework for a detailed list of different emission factors available (Smart Freight Centre, 2016).

[15] This database was built from four related datasets of freight flows through the different links:

- Freight shipped out from factories in China to either the transload facility (TSLD) or Mira Loma stocking distribution center (SDC) in Southern California (China drayage and U.S. drayage links).
- Freight shipped from TSLD to SDCs and rapid deloyment centers, or RDCs (U.S. inland link).
- Freight shipped from SDCs (only products shipped via Los Angeles and Long Beach) to THD stores (SDC to store link).
- Freight shipped from RDCs (only products shipped via Los Angeles and Long Beach) to THD stores (RDC to store link).

- **Fuel efficiency and emission factors.** THD provided carrier-specific data based on its SmartWay data, which allowed the calculation of fuel efficiency and emission factors specific to THD operations. This is more accurate than industry average values. More importantly, when compared with industry averages, these fuel efficiency and emission factors show the impact of current technologies and strategies adopted by truck carriers working for THD. In the case of Chinese carriers, industry averages were used based on information from local carriers.
- **Ancillary data.** THD provided further details to estimate emissions in the supply chain. An example is a list of physical characteristics for each product containing information such as weight and volume per packaged unit. Other data in this category includes the exact addresses of factories in China, distribution centers, and stores in the United States.

Given data availability, specifically regarding fuel efficiency and emission factors and its variability, this study uses different approaches to estimate emissions and energy consumption for truck (Figure A2) and rail (Figure A3). The first step in calculating emissions was to identify the specific origin-destination pairs served by truck or rail. This was a straightforward task, because all land-based links are trucking-only except for the U.S. inland link. In the U.S. inland link, two SDCs (Dallas and Baytown) and three RDCs (Dallas, Houston, and Topeka) are served by rail, whereas two SDCs (Mira Loma and Lathrop) and four RDCs (Ontario, Redlands, Tolleson, and Tracy) are served by trucks.

Truck operations

Figure A2 illustrates the calculation methods for truck operations, which consist of the following:

1. Names of specific carriers were used to develop NO_x and PM emission factors in g/km and fuel efficiency in L/100km based on THD's SmartWay submittals.[16]

2. After identifying the origin and destination for all routes, addresses provided by THD were used to geocode those points and obtain latitude and longitude coordinates. Those coordinates were used to estimate distance traveled on the

15 The type of shipment helps to identify the nodes to which containers are shipped.

16 This study does not use carrier-specific emission factors and fuel efficiency, but rather develops aggregate factors for those carriers transporting the products analyzed in this study. This ensures confidentiality of truck carriers while providing a more accurate characterization of truck technology used in THD's operations.

road network for the China drayage, U.S. drayage, and U.S. inland links.[17] For the SDC/RDC to store links, the great circle distance was used instead.[18] The result of this process was specific distance for all routes traveled within each link in the supply chain.

3. Using products' dimensional database, the volume of the products traveling in each trailer/container was calculated. That volume was then compared with the total volume available in each trailer or container, depending on its size. This allowed the allocation of the full equipment fuel consumption and emissions to specific products.

NO_x and PM emissions by trip associated with each trailer/container were calculated using the results of steps 1 and 2, by multiplying each emission factor by the distance traveled. For CO_2 emissions, the total fuel consumed was calculated first, and then multiplied by the CO_2 content of diesel (2,684 grams of CO_2 per liter). This process was conducted for every truck shipment, so emissions associated are at the truck level. Using results from step 3, shipments containing only products from the three analyzed suppliers were assigned with 100% of the calculated emissions; in all other cases, emissions were assigned based on the percentage volume share occupied only by the three suppliers' products. Lastly, total emissions were the sum of all individual shipments. Specific data sources are provided in Table A1.

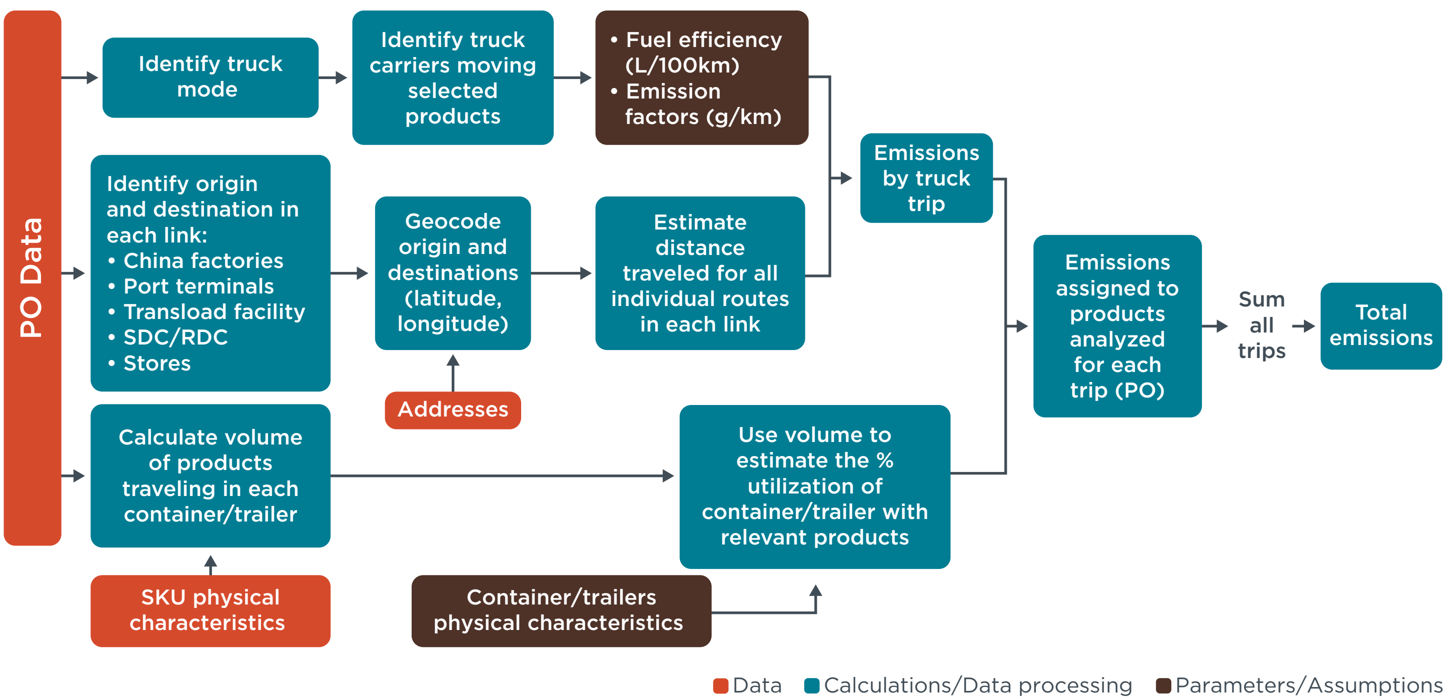

Figure A2. Calculation methods for truck operations

17 This analysis was based on the Google My Maps application, which suggests the most direct route between two points. Although some truck traffic might be restricted on some of the suggested routes, this study assumes these values as a conservative approach of the distance traveled and a better measure than the great circle distance.

18 The great circle distance represents the shortest distance between two points on the surface of a sphere. For this study, this represents the "straight-line" distance between the SDC/RDC and THD's stores. Using this approach allowed streamlining the calculations as opposed to optimizing the routes on the road network for 600 stores and 11 SDCs/RDCs.

Rail operations

Rail calculations were similar to truck calculations, but they differed in the level of disaggregation. Figure A3 illustrates the calculation methods for rail operations, which consist of the following:

1. Emission factors are obtained for rail operations in the United States, and they are based on sector-wide inventories. Such inventories use data for a given period on total distance traveled, total weight transported, and total fuel consumed. Then, using fuel-specific carbon content and engine emissions specifications, industry average emission factors (g/tonne-km) were developed. This study collected rail emission factors from different sources depending on the scenario and type of technology. This approach was not as detailed as the truck mode; however, it is expected that results are still robust, as the rail industry is considerably more homogenous and there are only a handful of rail carriers providing services on the analyzed routes.

2. This step involves the use of geocoded addresses to estimate the distance between the TSLD and the SDCs and RDCs served by rail.

3. Given the type of emission factors, estimating product volume on each rail box was not necessary. Instead, weight of cargo was estimated for each shipment and then aggregated by origin and destination pair.

The distance obtained in step 2 was multiplied by weight in step 3. This resulted in total freight activity (tonne-km) for each route served by rail. A straightforward last step was to multiply freight activity by CO_2, NO_x, and PM emission factors to obtain total emissions from the rail mode. Specific data sources are provided in Table A1.

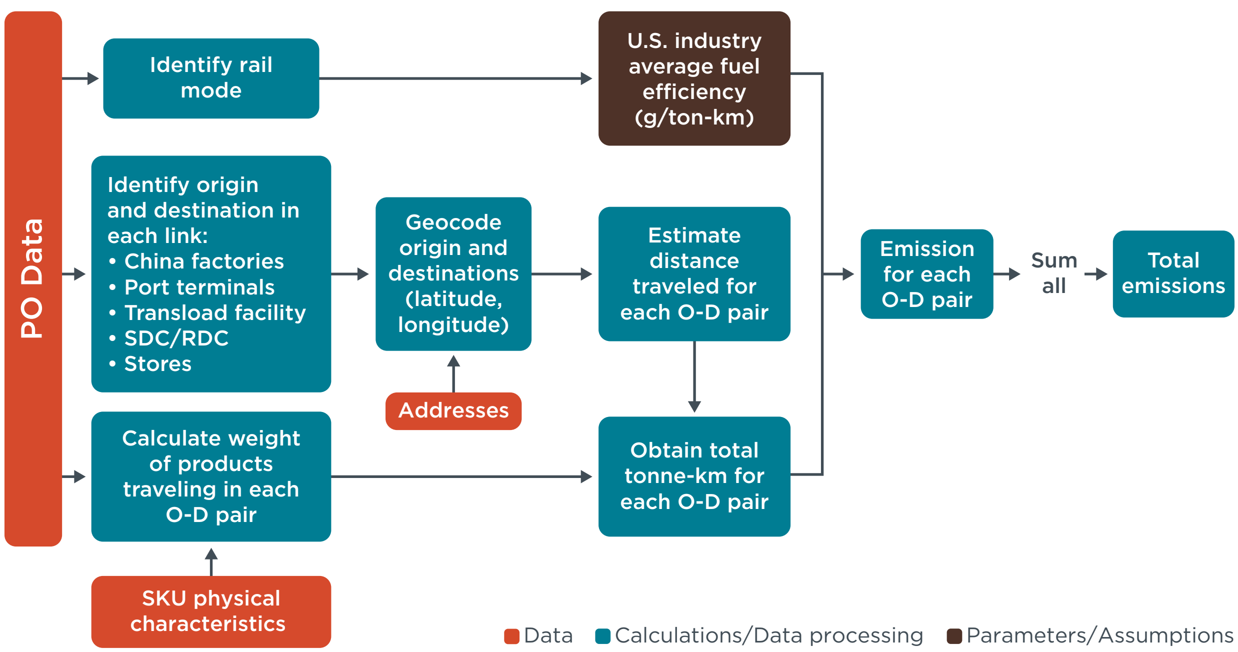

Figure A3. Calculation methods for rail operations

Table A1. Summary of data sources

Data	Description	Model use	Source
Purchase orders in 2017 (PO data)	Data of all products ordered from three Chinese suppliers shipped to U.S. stores through the ports of Shenzhen and Los Angeles and Long Beach.	Define nodes and links and estimate freight traffic for China drayage and U.S. drayage links.	The Home Depot
	Data of all products ordered from three Chinese suppliers shipped from the TSLD in South Gate, CA to the SDC and RDC networks.	Define specific routes and estimate freight traffic for the U.S. inland link.	The Home Depot
	Data of all products ordered from three Chinese suppliers shipped from the SDC and RDC network to 600+ U.S. stores (only stores receiving Los Angeles and Long Beach inbound freight).	Define specific routes and estimate freight traffic for the SDC to store and RDC to store links.	The Home Depot
SKU characteristics	Details the SKU ID, supplier, volume, and weight of the 228 different products shipped by the selected suppliers.	Calculate volume and weight of shipped products.	The Home Depot
Addresses	Exact address of Chinese factories, TSLD, SDCs, RDCs and more than 600 THD stores.	Geolocation of the different nodes and estimation of traveled distance by truck or rail.	The Home Depot
Truck fuel efficiency and emission factors in *Conventional* scenario	China: • Emission factors for average fleet heavy-duty trucks in China. • Fuel consumption rates meeting China fuel consumption standard stage 1, based on engine size, GVWR, average payload, and engine type. • Characteristics of average truck hired by suppliers in China.	Estimate fuel consumption and emissions at truck trip level in the *Conventional* scenario.	Emission factors (Cui et al., 2018) Fuel efficiency modeled by ICCT based on truck characteristics for equipment used by Chinese suppliers.
	United States (all land-based links) • Average fuel efficiency and emission factors for non-SmartWay partner truck carriers.	Estimate fuel consumption and emissions at truck trip level in the *Conventional* scenario.	SmartWay public data for non-SmartWay carrier partners.
Truck fuel efficiency and emission factors in *Green* scenario	China: • Emission factors for China V emissions standard. • ICCT modeled fuel consumption of trucks in this link, based on engine size, GVWR, average payload, and fuel type. • Characteristics of average truck hired by THD suppliers in China.	Estimate fuel consumption and emissions at truck trip level in the *Green* scenario.	• Emission factors (Cui et al., 2018) • Fuel efficiency modeled by ICCT based on truck characteristics for equipment used by Chinese suppliers.
	United States (all land-based links) • Average fuel efficiency and emission factors for truck carriers hired by THD moving the analysed products.	Estimate fuel consumption and emissions at truck trip level in the *Green* scenario.	• THD's SmartWay data aggregated by U.S. EPA to protect data confidentiality
Truck fuel efficiency and emission factors in *Green Plus* scenario	China: • Emission factors for China VI emissions standard. • Fuel consumption rates meeting China fuel consumption standard stage 3, based on engine size, GVWR, average payload, and engine type. • Characteristics of average truck hired by suppliers in China.	Estimate fuel consumption and emissions at truck trip level in the *Green Plus* scenario.	• Emission factors (Cui et al., 2018) • Fuel efficiency modeled by ICCT based on truck characteristics for equipment used by Chinese suppliers.
	United States (all land-based links) • Emission factors for U.S. EPA 2010 emissions standard. • Technology potential for fuel consumption improvement	Estimate fuel consumption and emissions at truck trip level in the *Green Plus* scenario.	• Emission factors (U.S. EPA, 2016) • Fuel efficiency (Delgado et al., 2016)
Rail fuel efficiency and emission factors	• Emission factors in g/tonne-km for CO_2, NO_X, and PM by rail technology.	Estimate fuel consumption and emissions by rail route.	• Tier 2: values for rail industry average (U.S. EPA., 2017) • Tier 4: (Gladstein, Neandross & Associates, 2013b) • Tier 4 LNG: (Gladstein, Neandross & Associates, 2013b) • Tier 4 LNG + EV: (Cambridge Systematics, 2012)

MARINE METHODS

- *Green* scenario is modeled using actual data
  - THD provided purchase order data with details of ships deployed in 2017 to move the selected products analyzed in this study. This study assumes the same group of ships were used in 2015, as the most up-to-date data used in the SAVE model is from 2015.
  - This study uses ICCT's SAVE model and retrieves the specific ships' annual emissions profile. Emissions of CO_2, SO_x, NO_x, and $PM_{2.5}$ are included.
  - The SAVE model uses actual Automatic Identification System data in 2015 (hourly, global coverage) to calculate ships' annual emissions profiles.
- The SAVE model also outputs cruising hours and average cruising speed, to be used to construct strategy assumptions for other scenarios.
- The fleet characteristics of THD-deployed ships are used to construct strategy assumptions for other scenarios.
- The assumptions regarding the efficiency improvement rate of different combinations of ship technology was referenced from a previous ICCT paper (Wang & Lutsey, 2013), which estimated a range of 20%–40% improvement by 2020 compared with 2012, and 30%–55% improvement by 2030.

As a first step, this study calculates a hypothetical representative ship using the characteristics of the 103 container ships deployed by THD in 2017:

- Cargo capacity: The amount of cargo in tonnes that the ship can carry in one voyage. This is calculated as an average TEU across the 103 vessels, converted to tonnes. We assume that the ship is 70% loaded and each TEU weighs 10 tonnes.
- Speed: The average cruising speed over the marine link, which is about 16 knots. This is calculated as an average cruising speed of the 103 vessels.
- Cruise time: Time spent over the marine link when cruising. This is calculated by dividing the length of the marine link by the average cruising speed.
- Berth time: Time spent while berthing at the departure and arrival ports. This is referenced from the most recent emissions inventory reports published by the two ports. For Shenzhen, the 2015 emissions inventory indicates an average at-berth period of 14 hours for container ships, while for Long Beach/Los Angeles, the 2017 emissions inventory reported 73 hours on average.
- Anchorage time: Time spent while anchoring at the departure and arrival ports. This is referenced from the 2017 emissions inventory reports published by the two ports.
- CO_2 rate: CO_2 emission rate of the representative ship. This is calculated as an average CO_2 emission rate across the 103 vessels. The CO_2 emission rate of each vessel is calculated by dividing annual CO_2 emissions by annual activity hours.
- Voyage CO_2: The amount of CO_2 emissions emitted over the marine link for one voyage. This is calculated by multiplying the CO_2 emission rate by the hours spent over the marine link, which is the sum of cruise, berth, and anchorage time.
- N trip: The total number of trips made by the ship annually. This is an average of total number of trips made by the 103 vessels, which was three trips in 2015 based on the SAVE model.

» THD CO_2: Annual CO_2 emissions associated with moving THD products. This is calculated by multiplying voyage CO_2 emissions with annual voyage numbers and apportioning them by weight of THD products.

Second, this study develops a series of impact factors for each strategy in each scenario. The impact factors are calculated as if each strategy were implemented independently of other strategies. The overall impact is a product of all the impact factors. Take the long-term *Green Plus* scenario as an example. The shore power strategy would reduce CO_2 emissions while at berth; the scheduling strategy would reduce anchor time and CO_2 emissions; the ship size strategy would increase cargo capacity and lower CO_2 emissions; and the ship improvement strategy would reduce CO_2 emissions directly. The individual impact factors are 0.85, 0.56, 0.99 and 1 (0.996), respectively, compared with *Green* scenario. The overall impact would be 0.47, which means the overall CO_2 emissions would be reduced by about 53% for the long-term *Green Plus* scenario compared with the *Green* scenario.

APPENDIX B. LITERATURE REVIEW

The literature review frames this study in a body of research broadly about freight and supply chain energy and environmental performance. There is no shortage of work addressing different aspects of the supply chain and its connection to freight and sustainability. Current literature falls within the following types of studies:

- **Case studies** focus on the analysis of specific strategies, modes of transportation, or single segments in a supply chain. Given their specificity, case studies normally rely on detailed data, and they mostly address the impacts of a specific strategy, rather than a set of possible strategies or alternative pathways.
- **Best practice surveys** provide information about different strategies to reduce emissions in general supply chains. Normally, these studies present an extensive list of strategies and their associated/potential emission reductions. Nonetheless, much of the impact assessment is gathered through literature review or second-hand data.
- **Modeling research** consists of studies using an analytical framework in combination with data, mainly aggregated, to evaluate freight performance. It is common for these studies to compromise on their scope, either focusing on a specific aspect of the supply chain or on data granularity. Modeling research intersects with case studies or best practice surveys whenever a modeling framework is applied.
- **Emission assessment guidelines/methodologies** consist of documents laying out the procedures to calculate supply chain emissions. These documents highlight the relevance of streamlining data collection and tracking industry performance to identify the most effective strategies. In many cases, these documents include collaboration with specific shippers and carriers to provide feedback and test the methodology.
- **Broader supply chain studies** consist of analyses exploring sustainability issues beyond transportation impacts, such as inputs sourcing, product recycling, buildings' energy efficiency, responsible water usage, manufacturing energy intensity, etc. These studies can be framed within larger analyses focusing on the economic, financial, and social aspects of the supply chain.

Table B1 summarizes the studies analyzed in this literature review. This sample attempts to grasp the trends in the research of supply chain and transportation rather than being an exhaustive literature review.

Table B1. Literature review

Title	Type of Study	Author Year	Region	Scope	Summary
The economic and environmental benefits of increasing maximum truck weight: the British experience	Modeling research Case study	McKinnon, 2005	United Kingdom	Trucking	Estimates the reduction of truck-km traveled due to switching to larger/heavier trucks (38 to 44 tonnes). Findings suggests that consolidation into larger trucks would yield net energy and emission savings.
Truck Empty Backhaul	Modeling research Case study	Florida Department of Transportation, 2018	Florida, U.S.	Trucking	Evaluates truck empty backhaul in Florida using weigh in motion data. The report presents a very detailed assessment of the factors influencing empty backhaul, imbalance flow, regulatory restraints, demographics, cargo/equipment specialization, among others.
Analysis of Transport Efficiency in the U.K. Food Supply Chain	Modeling research Case study	McKinnon et al., 2003	United Kingdom	Trucking	Develops key performance indicators (energy consumption) based on a survey to 2,000 carriers in the food industry. The study aims at benchmarking the performance of those carriers and highlights the potential strategies to improve efficiency.
Destination Sustainability: Reducing Greenhouse Gas Emissions from Freight Transportation in North America	Best practice survey	Commission for Environmental Cooperation, 2011	North America	Trucking Rail	Presents the results of a large-scale consultation process among key stakeholders in Canada, Mexico and the United States to identify key action toward the reduction of freight emissions. In addition to addressing technology and operations, the report also highlights strategies such as carbon pricing, land use planning, and infrastructure funding.
Freight Transport in a Low-Carbon World: Assessing Opportunities for Cutting Emissions	Best practice survey	McKinnon, 2016	Global	All transport modes	Discusses five key areas to reduce freight's carbon intensity: supply chain structure, modal split, vehicle utilization, energy efficiency, and energy mix.
Supply Chain Decarbonization: The Role of Logistics and Transport in Reducing Supply Chain Carbon Emissions	Best practice survey	World Economic Forum, 2009	Global	All transport modes Input sourcing Manufacturing Building emissions	Explores decarbonization opportunities across the supply chain, from low-carbon sourcing in agriculture and packing strategies to road congestion reduction. It presents high-level mitigation potential based on previous studies.
Transitioning to a Zero or Near-Zero Emission Line-Haul Freight Rail System in California	Modeling research Best practice survey	RailTEC, 2016	California U.S.	Rail	Examines the challenges and opportunities of transitioning from conventional diesel-electric to zero or near-zero emission line-haul freight rail in California. The study develops two scenarios: one with a smaller captive fleet of advanced technology freight locomotives in the Southern California Air Basin, and other for a national fleet. In each scenario a set of suitable technologies for the type of operations is assessed.
Decarbonizing Maritime Transport Pathways to zero-carbon shipping by 2035	Modeling research Best practice survey	ITF, 2018	Global	Marine	Analyzes technologies, fuels and operational improvements needed to reach a zero-emission target in the marine sector by 2035. The study uses ITF's general equilibrium freight model.
Moving California Forward: Zero and Low-Emission Goods Movement Pathways	Modeling research Best practice survey	Gladstein, Neandross & Associates, 2013a	California, U.S.	All modes	Develops a comprehensive evaluation of the different trajectories to reduce freight emissions in California. The report presents the impact of specific strategies classified in three levels of operation: near-dock drayage, regional, and statewide strategies.
Supply Chain Perspectives and Issues. A Literature Review	Broader supply chain study	Park, Nayyar, and Low, 2013	Global	Economic perspectives Business Services Trade policy Trade finance Sustainability	Presents a comprehensive review of critical supply chain issues from economic and business perspective to value-added, new entrants, and sustainability. It highlights the complexity and the different aspects affecting a company's supply chain.
GLEC Framework for Logistics Emissions Accounting and Reporting	Emission assessment guidelines/ methodologies	Smart Freight Centre, 2019	Global	All modes	Develops a framework to harmonize the different methodologies for emissions accounting across different sectors. It aims at consolidating one single methodology to guide companies not only to calculate comparable metrics, but also on data collection, performance tracking, and informed decision-making.
Clean Cargo Working Group Carbon Emissions Accounting Methodology	Emission assessment guidelines/ methodologies	Business for Social Responsibility, 2015	Global	Marine	Describes the CO_2 emission accounting methodology for ocean carriers. Because it was developed by the Clean Cargo Working Group, composed of the leading shipping lines, this methodology represents the standard for the industry.
Calculating GHG emissions for freight forwarding and logistics services	Emission assessment guidelines/ methodologies	Schmied and Knörr, 2012	Europe	All transport modes	Provides a guide on how to calculate CO_2 emissions from freight according to the EN 16258 standard from the European Committee for Standardization.
The Green Freight Handbook	Emission assessment guidelines/ methodologies	Mathers et al., 2014 (Environmental Defense Fund)	Global	All transport modes	Provides a framework for businesses to calculate their CO_2 emissions and establish metrics to identify areas of opportunity. The methodology aims at raising company awareness about ways to reduce emissions while saving on transportation costs.

The complexity of supply chain research and the urgency behind efforts to evaluate supply chain and transportation performance may explain the many emissions assessment guidelines and methodologies that attempt to streamline this process. This study opts to be consistent with the GLEC framework for logistics emissions methodologies because it has the most relevant combination of technical rigor, flexibility to match the level of data availability, and industry input.

Figure B1 illustrates where these different types of studies fall in the spectrum of geographic coverage, strategy coverage, mode coverage, level of data disaggregation, applicability to the transportation sector's sustainability, and applicability to other supply chains. While most study types have trade-offs across these elements, this study is designed to be comprehensive in terms of geographic, strategy, and mode coverage; to rely on very detailed and disaggregated data; and to be highly applicable to the advancement of transportation sustainability. One area where this study might fall short is in its applicability to other supply chains, as that will depend on geographic coverage and supply chain characterization. Modeling research and methodologies are not considered, due to their often-theoretical nature.

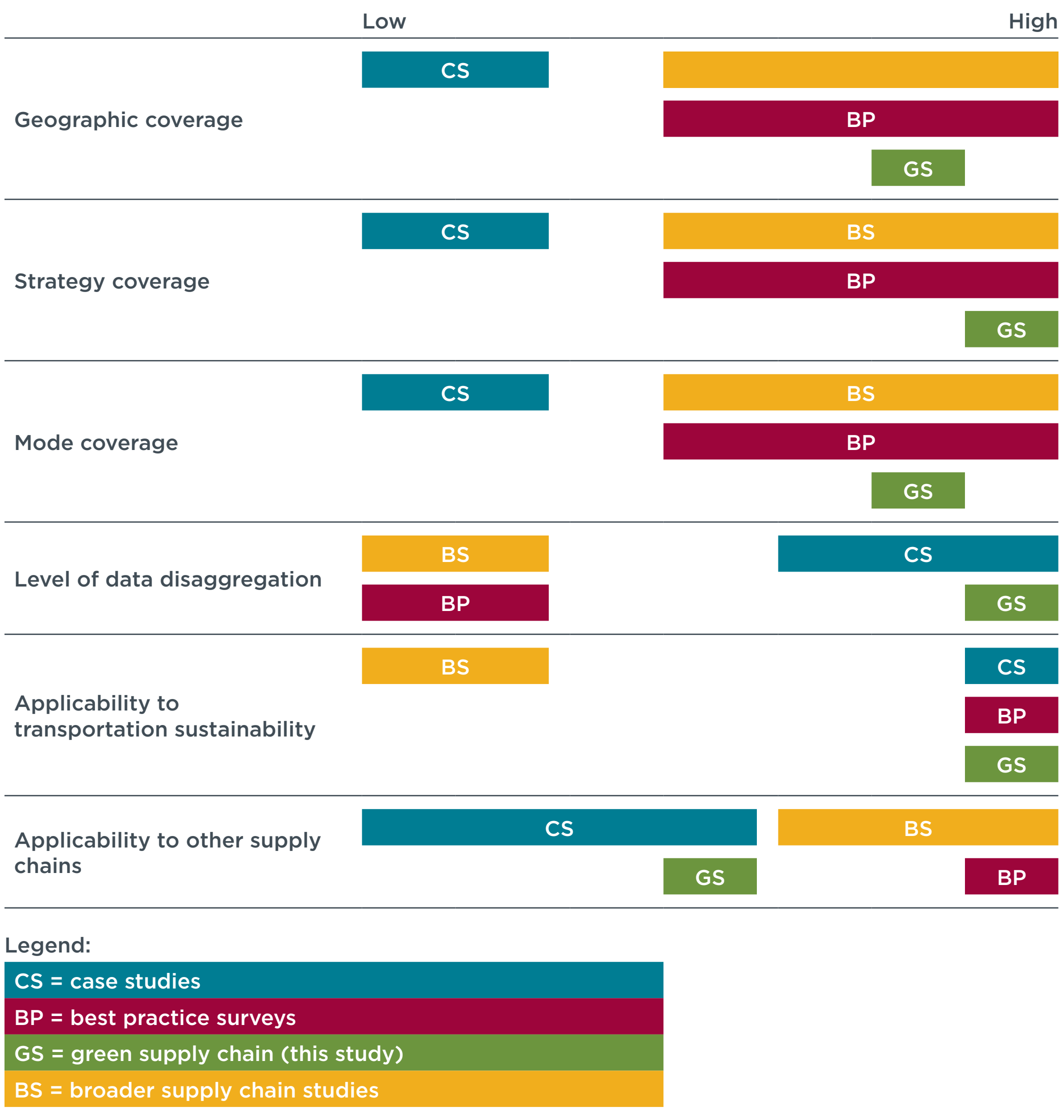

Figure B1. Literature review framework

Case studies are based on specific data and thus present robust conclusions, which are often applicable only to a limited set of regions, strategies, and modes. Best practice surveys provide a more comprehensive perspective of regions and strategies across many modes. Nonetheless, because of the lack of quantitative results or very simplified results, these surveys can typically provide only general guidance about the most effective strategies to reduce emissions and energy consumption. Broader supply chain studies can ideally be comprehensive in terms of geography, strategy, and mode coverage, but they often do not rely on as-detailed data for the transportation sector and thus have limited applicability to the transportation sector.

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