Freight Transport

Daniela Rivera Mirabal, Austin Sonnier, Henry Strecker

Baseline scenario

Based on our projections for the baseline scenario, the sector sees an overall increase in demand of 42% from 2022 to 2050. The primary driver behind this overall increase in demand is the rail sector which is projected to increase by nearly 1 trillion annual ton-miles, an increase of 57% from 2022. Trucking follows close behind by adding 550 billion ton-miles by 2050, a 37% increase from 2022. The service that is expected to see the greatest proportion increase is aviation at 66%. Despite this large potential for growth, it would remain the lowest magnitude of demand for ton-miles when compared to the rest of the sector. Inland water is expected to have minimal growth over this time period, increasing by 13% and about 55 billion ton-miles.

The variance in the demand for additional ton-miles across all technologies determines our projections for emissions and primary energy use. Since this is the baseline scenario, the primary energy and emissions are based on the current fuel, technologies, and efficiencies. Trucking contributes to about 80% of greenhouse gas emissions emitted from this sector for the whole time period we are looking at. All other technologies pale in comparison for emissions, but it is important to note that aviation is the next largest emitter with 14% of the total share. Freight via aviation carries with it emissions that are almost 5 times more intense than trucking per ton-mile. Trucking is still over 10 times worse than rail and inland water, the two most efficient technologies with regards to emissions. When looking at primary energy use, we see practically the exact same trends as we did with greenhouse emissions. The overall increases in demand are at a near constant rate after 2025, as is the result of the projection.

Figure 1: Baseline Scenario Ton-mile Demand

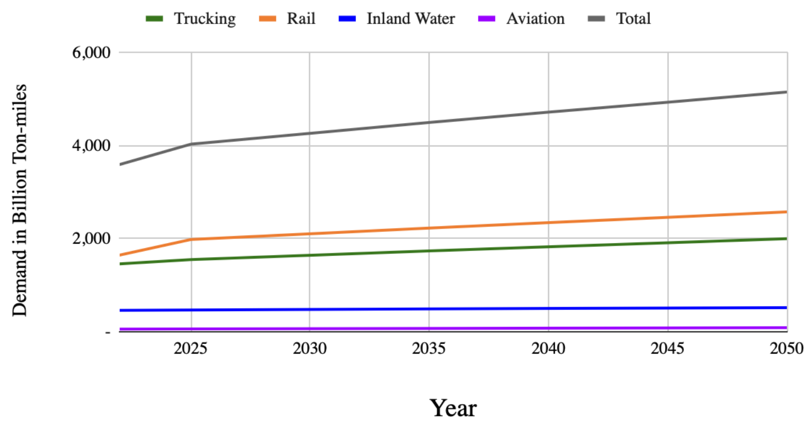


Figure 2: Baseline Scenario GHG Emissions

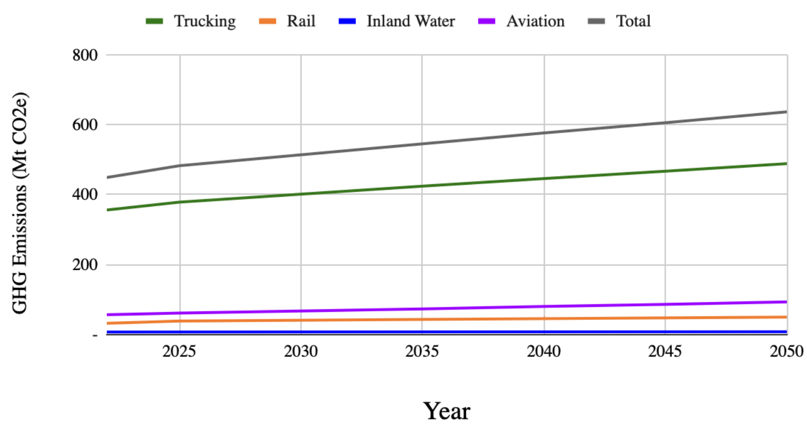
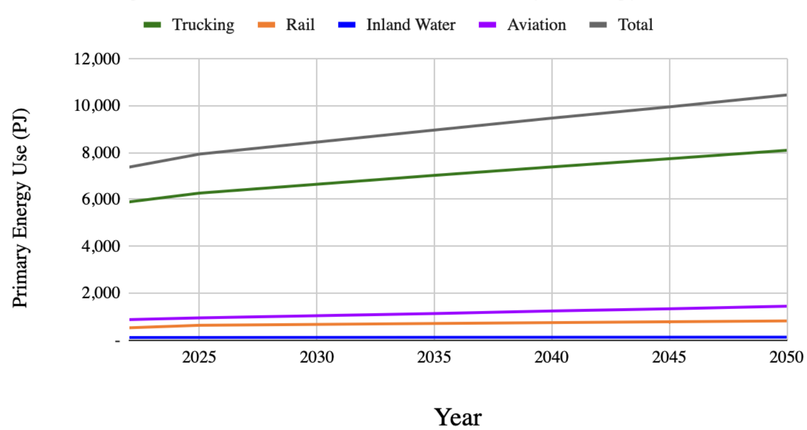


Figure 3: Baseline Scenario Primary Energy Use



Freight Transport

Daniela Rivera Mirabal, Austin Sonnier, Henry Strecker

Proposed strategies in the Low Energy and Emissions Scenario (LEES)

Strategy	Description, justification, and adoption level	TBC	ASI
Electric Trucks	Electrification of heavy-duty trucks (HDTs) is critical to achieving sustainability and carbon neutrality in road freight By 2050, 99% of electric MD/HD truck sales will be zero emission vehicles. A majority of those will be battery electric vehicles (BEVs). According to an NREL study by Ledna, et al (2022), 20% of HD/MD trucks will still be internal combustion engine vehicles (ICEVs) (Ledna 2022). One of the main benefits of BEVs is their high energy efficiency and low well-to-wheel (WTW) GHG emissions. Zhou et al. (2017) found that BEV trucks can reduce WTW GHG emissions by 85% compared to diesel trucks, and also have a lower life-cycle cost. This is because electric motors have a much higher conversion efficiency than internal combustion engines, and electric vehicles can use renewable sources of electricity, such as solar, wind, or hydro, to charge their batteries. Albatayneh (2020) confirmed that electric drive trains are much more efficient than liquid-fuelled engines, with an average efficiency of 47.06% versus 15.32%. Furthermore, electric vehicles have regenerative braking, which recovers some of the kinetic energy that would otherwise be wasted as heat when braking, and converts it back into electrical energy to recharge the batteries. Therefore, electric trucks are more energy efficient and emit less carbon dioxide than conventional trucks. Electrification of MD/HD trucks is critical for achieving sustainability and carbon neutrality in road freight, and also for enhancing the competitiveness and profitability of the trucking industry. However, there are still some challenges and barriers to the widespread adoption of electric trucks, such as the availability and affordability of charging infrastructure, the range and weight of batteries, the reliability and durability of electric components, and the consumer and regulatory acceptance of electric vehicles. These challenges require further research and development, as well as policy and market support, to overcome them and accelerate the transition to a low-carbon and sustainable freight transportation system.	T	S
High Capacity Utilization	High capacity utilization can apply to all trucks in the transportation sector. By 2050, this can reduce overall CO_2 emissions by up to 9%. Capacity utilization is the ratio of the weight of the cargo carried by a truck to its maximum capacity. Higher capacity utilization means that trucks are carrying more cargo per trip, which can improve efficiencies in the trucking industry and reduce carbon emissions. Some technologies that will enable higher capacity utilization artificial Intelligence automation and supply chain software. This can reduce emissions by enabling better load planning and matching, which can increase the capacity utilization of trucks and reduce the number of empty or partially loaded trips. For instance, The Home Depot estimates that it has achieved container capacity utilization of 85% using such software, compared with 75% utilization previously achieved without it	BT	I
Smart Supply Chain Logistics	A popular tool for smart logistics is automatic identification which includes radio frequency identification (RFID), barcodes, and biometrics that can identify and track objects, people, and animals. This can reduce emissions by minimizing errors, delays, and losses in the supply chain, which can reduce the need for extra trips, returns, or replacements. It can also help monitor and control the temperature, humidity, and quality of goods, which can reduce spoilage and waste. Another tool in the smart logistics realm are autonomous vehicles which can reduce emissions by avoiding unnecessary stops, idling, and acceleration, as well as by following optimal routes and speeds.	BT	I
Reduce Food Waste	The USDA pledge to reduce food waste by 50% by 2030 is a national goal that was announced in 2015 by the USDA, EPA, and FDA. It aims to cut food loss and waste in half by the year 2030, which would reduce greenhouse gas emissions, save money, and improve food security. The USDA, EPA, and FDA have released a draft National Strategy for Reducing Food Loss and Waste and Recycling Organics, which outlines four main objectives and actions to achieve the goal (USDA, 2023).	B	A

Freight Transport

Daniela Rivera Mirabal, Austin Sonnier, Henry Strecker

Shift Trucking Ton-Miles to Rail Ton-Miles	This strategy involves moving some of the freight that is currently transported by trucks to rail, which is more energy-efficient and less carbon-intensive. According to the U.S. Energy Information Administration, rail transport uses about four times less energy per ton-mile than truck transport1. This means that shifting 25% of trucking ton-miles to rail ton-miles could reduce freight sector fuel consumption and emissions by approximately 3-4% by 2050 (EIA, 2020). According to the same EIA report as well as the Association of American Railroads, rail transport uses about four times less energy per ton-mile than truck transport. This means that for every ton of freight moved over one mile, rail transport consumes only 25% of the energy that truck transport does. Rail transport is also more energy-efficient than truck transport because it has lower aerodynamic drag, rolling resistance (steel on steel versus rubber on pavement), and engine idling losses.	B	A
Shifting ton-miles from aviation to train	Flights that travel more than 2000 miles long have particularly high emissions associated with them because the planes are typically larger and thus require more fuel. We would force a shift of these high-emitting trips to be carried out via railways. The US Census Bureau recorded statistics on air freight categorized by distance thresholds, and flights over 2,000 miles accounted for over 20% of the total activity in the sector. Our resulting action is to reduce air freight by 20% by shifting these ton-miles directly to the more efficient rail system.	B	A
Shift from diesel locomotive to electric locomotive engines	This LEES strategy involves replacing the diesel engines that power most of the freight and passenger locomotives in the U.S. with electric motors that draw electricity from overhead wires or batteries. Electric locomotives are more energy-efficient and less carbon-intensive than diesel locomotives, as they have lower fuel consumption, lower emissions, and higher power output. A switch to battery-electric freight will cut the industry's annual carbon dioxide emission by more than half, eliminating more than 400 million metric tons of carbon dioxide in 20 years (Popovich, 2021)	T	S
Implement sustainable aviation fuel (SAF)	Sustainable Aviation Fuel (SAF) is a jet fuel alternative that carries with it drastically reduced emissions and is thus desirable for the aviation sector to adopt. The limiting factor in its adoption is production. Goals have been set to increase our current production of ~200 million gallons per year to 3 billion gallons by 2030, and ultimately 36 billion gallons per year in 2050 to cover the whole sector. When compared to conventional jet fuel, SAF reduces greenhouse emissions by 90% based on cellulosic biocrops.	T	S
Increase Aviation average stock engine efficiency	Historically we have seen advancements in fuel efficiency for aviation, and it is reasonable to expect these trends to continue into the future. A report from Aviation Benefits Beyond Borders quantified that rolling improvements in the field are 2.3% per year. Our team will assume improvements on the order of 1.5% per year because the trend appears to be on a small decline.	T	I
Electrify short distance aviation freight (< 250 miles)	Short distance aviation has the opportunity to be electrified, which will have major impacts with the efficiency gained in grid development. This shift once again uses freight data from the US Census Bureau, which reported that 15% of all air freight is on trips shorter than 250 miles. Our LEES will incorporate a slow implementation of air freight technology based on the Pyka Pelican aircraft. It should be expected that electrified aviation will improve in the coming years, perhaps with greater range, but we set this specific model as our baseline for projections.	T	S
Small-fleet shipping electrification	There are approximately 1,000 vessels that fall in the category of fleet boats. The functionality of these boats is to transport shipping containers from the docks to barges set up in the middle of the river. A report from the American Bureau of Shipping and Vanderbilt outlined that fleet boats contribute an estimated 20% of the industry's emissions and fuel consumption. A conversion to electric engines would drastically reduce the impact these ships have, and is attainable due to the limited number of fleet boats.	T	S
Ammonia and renewable fuels for water	The American Bureau of Shipping released a whitepaper on the use of biofuels in the inland water freight industry in 2021 that was informative on the projected use of marine gas oil (MGO) alternatives. The largest projected share of alternative fuel comes from ammonia. Ammonia is a less energy dense green alternative to MGO that carries with it very low emissions. It was projected that by 2050, 35% of the industry's vehicles would be fueled by ammonia/hydrogen, so we decided to lean more heavily on ammonia and get that share to 30% by 2050. We closely followed the ABS report to project for all years in our study.	T	S

Freight Transport

Daniela Rivera Mirabal, Austin Sonnier, Henry Strecker

Proposed policies in the LEES

Policy description	Applicable to the following strategies
Carbon tax: The policy being implemented is Executive Order 14037 of August 5, 2021, “Strengthening American Leadership in Clean Cars and Trucks,” 86 Federal Register 43583A. This executive order focuses on carbon tax as a policy that imposes a fee on the carbon content of the fuel used by medium and heavy duty truck freight sector. The fee is based on the amount of carbon dioxide (CO2) that is emitted when the fuel is burned (Lattanzio, 2023). The carbon tax increases the price of gasoline and diesel, which creates an incentive for fuel efficiency and emission reduction. The carbon tax also generates revenue that can be used for various purposes, such as reducing other taxes, investing in clean energy, or compensating low-income households. A carbon tax is considered a market-based approach to address the negative externalities of carbon pollution. One example of a carbon tax policy is the one implemented by Canada, which applies to all provinces and territories that do not have their own carbon pricing systems. The carbon tax rates are set to increase from $65 per tonne of CO2e in 2023 to $170 per tonne by 2030 (Canada Revenue Agency, 2021).	Electricity based freight modes of transport (Electric Trucks, Electric Train, Electric Plane)
High Capacity Utilization: There are policy headwinds to achieving better capacity utilization rates in the trucking sector. Policy headwinds include laws such as those discussed in a report to congress titled Truck Size and Weight: Compilation of Existing State Truck Size and Weight Limit Laws. For instance, the Federal gross vehicle weight limit is 80,000 pounds, the single axle weight limit is 20,000 pounds, and the tandem axle weight limit is 34,000 pounds (FHA, 2015). Ameliorating restrictions on weight discussed in the Federal Highway Administration's report to congress will save ton-miles and reduce carbon emissions.	High capacity utilization (trucking)
ICE sales ban: The California ICE vehicles sales ban is a policy that prohibits the sale of new passenger cars and trucks that run on gasoline or diesel in the state by 2035. The policy aims to reduce greenhouse gas emissions, improve air quality, and promote the adoption of zero-emission vehicles, such as electric or hydrogen fuel cell cars. The policy was announced by Governor Gavin Newsom in September 2020 and is part of the state’s broader efforts to combat climate change. The policy does not affect the sale or ownership of used ICE vehicles, nor does it apply to heavy-duty vehicles, such as trucks and buses, which have a separate target of 2045 for zero-emission sales.	Electrifying trucking
Inflation Reduction Act’s Advanced Technology Vehicles Manufacturing Loan Program This policy provides loans for projects that manufacture a range of advanced technology vehicles and their components, including light-duty vehicles, medium- and heavy-duty vehicles, locomotives, maritime vessels including offshore wind vessels, aircrafts, and hyperloop. The IRA specifies that funds may be used for the costs of providing direct loans for re-equipping, expanding, or establishing a manufacturing facility in the United States to produce, or for engineering integration performed in the United States of, newly authorized types of advanced technology vehicles only if those vehicles emit, under any possible operational mode or condition, low or zero exhaust emissions of greenhouse gasses.	Truck, Rail, Maritime
Food waste reduction: The USDA pledge to reduce food waste by 50% by 2030 is a national goal that was announced in 2015 by the USDA, EPA, and FDA. It aims to cut food loss and waste in half by the year 2030, which would reduce greenhouse gas emissions, save money, and improve food security. The USDA, EPA, and FDA have released a draft National Strategy for Reducing Food Loss and Waste and Recycling Organics, which outlines four main objectives and actions to achieve the goal (USDA, 2023). Objective 1: Prevent the loss of food where possible. Objective 2: Prevent the waste of food where possible. Objective 3: Increase the recycling rate for all organic waste. Objective 4: Support policies that incentivize and encourage food loss and waste prevention and organics recycling.	Food waste reduction
Railway Electrification (CORE) The railway electrification (CORE) in India is a policy that aims to electrify the entire broad gauge network of Indian Railways by December 2023. The policy is implemented by the Central Organisation for Railway	Electrifying rail

Electrification (CORE), which is the unit of Indian Railways responsible for electrification of the network. The policy is expected to reduce greenhouse gas emissions, improve energy security, and enhance the efficiency and cost-effectiveness of the railway sector (Ministry of Railways, 2020). The Government of India has set a target of 100% electrification of its broad gauge network by December 2023. The United States can study and adapt India's rail electrification policies to the United States railway system. The United States must be aggressive in banning diesel locomotives over 45 years old. In addition, all diesel locomotives must be taken offline and refurbished around their 25 year mark. At this point, it is recommended that the diesel engine be switched to battery electric or even catenary lines.	
The Electric or Low-Emitting Ferry Pilot Program is a federal program that provides grants for the purchase of electric or low-emitting ferries and the electrification of or other reduction of emissions from existing ferries. The program aims to support the adoption of zero-emission vessels, such as electric or hydrogen fuel cell ferries. The program was established by the Bipartisan Infrastructure Law of 2022 and is administered by the Federal Transit Administration (Federal Transit Administration, 2023)	Electrifying inland Water Shipping
The Greenship-K Promotion Strategy is a South Korean policy that aims to support the global green ship market by developing and popularizing emission-free technologies for the maritime sector. The policy was proposed by the Ministry of Oceans and Fisheries of South Korea in December 2020 and seeks to phase out greenhouse gas emissions by up to 70% by 2030. The policy covers various types of ships, such as electric, battery-hybrid, hydrogen, and LNG-fueled ships. The policy also provides incentives and support for the domestic shipbuilding and equipment industries to bolster their competitiveness and accelerate clean technology innovation in the marine shipping industry. The United States can study and adapt South Korea's innovative Greenship strategy (Korean Ministry of Oceans and Fisheries, 2020).	Inland Water Shipping
The Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), which requires airlines to offset any increase in their CO2 emissions above 2019 levels from 2021 to 2035. SAF fuels are eligible for generating emission reduction units under CORSIA, which can lower the offsetting costs for airlines (ICAO, 2023)	Biofuels for aviation
The Renewable Fuel Standard (RFS), which sets a target of 36 billion gallons of renewable fuel to be blended into transportation fuel by 2022. SAF fuels can qualify as advanced biofuels under the RFS and generate Renewable Identification Numbers (RINs), which can be traded or sold to meet the blending obligations. ("Sustainable Aviation Fuel Grand Challenge", n.d.)	Biofuels for aviation
"Electric only" aviation shipments on small aircraft going less than 250 miles A ban will be implemented by 2050 on non-electric aviation shipments under 250 miles. However, until then, this policy will establish standards and regulations for the safety, performance, and certification of electric or hybrid-electric planes, as well as the infrastructure and services required for their operation, such as charging stations, maintenance, and air traffic control. This policy also provides incentives and funding for the development and deployment of electric or hybrid-electric planes that can operate on short-haul routes, such as grants, loans, tax credits, or subsidies.	Electrifying aviation
Ban on ton-miles shipped over 1000 miles via truck and over 2000 miles for planes, and tax ton-miles shipped 500-1,000 miles for trucking. Shifting freight from truck and aviation to rail would require significant investments in rail infrastructure, technology, and operations, as well as incentives and regulations to encourage shippers and carriers to use rail. The U.S. government could also designate certain rail routes as green shipping corridors and provide subsidies, tax credits, or grants to rail operators and shippers who use them. The government could also impose stricter emission standards and fuel taxes on trucks that operate outside of these corridors, or require them to purchase carbon credits or offsets. Another possible way to implement this policy is to expand the use of intermodal transport, which combines different modes of transportation, such as truck and rail, to optimize efficiency and reduce costs and emissions. The government could support intermodal transport by investing in intermodal terminals, where freight can be transferred from one mode to another, and improving the connectivity and interoperability of different modes. The government could also offer incentives and discounts to shippers and carriers who use intermodal transport, or mandate a minimum percentage of intermodal freight for certain commodities or routes.	Shifting from trucking and aviation ton-miles to rail

Freight Transport

Daniela Rivera Mirabal, Austin Sonnier, Henry Strecker

Modeling description

Strategy	Modeling approach and key assumptions
High Capacity Utilization of Freight Trucks	**Temporal**: High capacity utilization has many market incentives to enable adoption, such as higher efficiency and profitability. Based on analytical trends (Source) and a home depot case study (source), a 9% reduction in CO_2 emissions by 2050 is possible. **Technology**: Artificial Intelligence automation and supply chain software **Deployment-limiting:** Easily accessible enterprise grade software with a highly skilled cadre of consultants and engineers to help with implementation. A limit is the Federal Highway Administration's regulation of the weight and size of truck shipments. **Policy**: Carbon tax, ameliorating the Federal Highway Administration's regulation on trucking capacity
Smart Logistics of Freight Truck Network	**Temporal**: Similar to high capacity utilization, smart logistics has many market incentives to enable adoption, such as higher efficiency and profitability. **Technology**: Radio frequency identification (RFID), barcodes, and biometrics. Autonomous vehicles **Deployment-limiting:** RFID, barcodes, and biometrics are more easily implemented due to an abundance of highly skilled consultants and engineers. Autonomous vehicles are more challenging to implement because of regulations such as the Federal Automated Vehicles Policy. There is also a lack of mature full self-driving (FSD) software for MD/HD trucks. FSD is currently being rolled out for light duty vehicles. **Policy**: A carbon tax on trucking emissions would incentivize the adoption of technologies such as smart logistics, that reduce carbon emissions.
Electrifying trucking fleet	**Temporal**: ZEV sales reach >99% by 2045, and 80% of the MD/HD stock transitions to ZEVs by 2050, reducing CO2 emissions by 69% from 2019. Due to a lack of hydrogen data and hydrogen infrastructure, our group only modeled BEV trucks (for both heavy and medium duty categories). This is a limitation that will be further discussed in the reflections section. **Technology**: According to NREL, BEVs tend to become cost-competitive for smaller trucks before 2030 and for short-haul (<500-mile) heavy trucks before 2035. **Deployment-limiting:** NREL's study, which states that heavy duty trucks can be battery electric by 2035 (for hauls less than 500 miles), informed our tax, ban, and shift policy. **Policy**: Trucking shipments above 500 miles and below 1000 miles will receive an additional tax to incentivize a shift to rail. Trucking shipments over 1000 miles will be banned and fully shifted to rail. **Additional Policies:** ICE Sales Ban, Inflation Reduction Act's Advanced Technology Vehicles Manufacturing Loan Program
Food waste reduction	**Temporal**: We assume that food waste in the US will be reduced from 40% to 20% by 2030 ("Food Waste FAQs", n.d.) and then will be maintained as 20% until 2050. We used the US Department of Transportation's projection for moving goods in the US ("Moving Goods in the United States", n.d.) to determine how much of the total ton-miles were food waste, and how much each transport sector ships (we found the 50% reduction in food waste would reduce 3% of the total ton-miles for trucking from 2030-2050). **Technology**: Ethylene absorbers, such as Bluapple, that can reduce the ripening and rotting of fruits and vegetables by capturing the ethylene gas they product. Food-sharing apps, such as Flashfood, that can connect consumers with discounted deals on food that is close to its best-by date, which can help prevent food waste at the retail level. Smart storage systems, such as Ovie Smarterware, that can monitor food freshness and alert consumers when food is about to expire. **Deployment-limiting:** N/A **Policy**: This is consistent with the USDA's food waste reduction pledge.
Shifting ton-miles from trucking/aviation to train	**Temporal**: We used the US Census' 2017 data for how many ton-miles each sector shipped, per distance shipped (United States Census Bureau 2023) and assumed the percentage of ton-miles shipped via each sector for each distance would stay the same through 2050. With this calculation we found that 390,540 million ton-miles (or 29%) of the trucking fleet in 2017 was shipped over 1,000 miles. We assumed 50% of the shipments from 500-1,000 miles would be shipped to rail by 2050, leading to a total of 41.2% of trucking ton-miles to be shifted to rail by 2050. We computed the percentage of ton-miles shifted each year using the compounded growth interest rate from 29% in

	2030 to 41.2% in 2050. Approximately 27% of all air freight trips are over 2,000 miles, so we decided to shift 20% of all air ton-miles to rail. These trips are generally higher emitting due to the weight of the cargo, so a shift to rail here would yield major greenhouse gas and energy reductions. **Technology**: N/A **Deployment-limiting:** We assumed the current rail system ("Freight Rail Overview | FRA" 2020) can handle all the trucking and aviation ton-miles we shifted. **Policy**: Ban on ton-miles shipped via trucking and aviation that exceed the distances outlined..
Shift from diesel locomotive to electric locomotive engines	**Temporal**: Diesel locomotive engines are refurbished every 20-30 years (Blaze 2020), so we assume 60% of vehicles will be refurbished at the 20 year mark and 100% by the 30 year mark. Because most diesel locomotives in the US are over 20 years old, we considered the current age of every locomotive (Vantuono 2022). We also assume after 2035 every locomotive over 45 years old will be electrified, or will be decommissioned and a new electric locomotive will be purchased. These assumptions led to calculating that by 2035: 48% of the fleet will be electrified, and 97.5% by 2050. **Technology**: We assume diesel motors can be quickly refurbished into battery-electric locomotives, as a case study in India proved to do in approximately 3 months (Jain 2018). We assume this current technology could be implemented in our current rail system, without the need of changing transport routes or shortening trips, as predicted by researchers in Lawrence Berkeley Lab (Popovich et al. 2021). We could also implement catenary lines, as has been already demonstrated in parts of the US (Walker 2013). **Deployment-limiting:** US Railroads Class 1 have spent over $250 billion in the past decade on infrastructure and equipment ("Freight Rail Investments - AAR", n.d.) and the cost of maintenance of an electric locomotive is 20-30% less than a diesel one (Nunno 2018). Therefore, we assume the environmental feasibility of electrifying current diesel locomotives. **Policy**: Our proposed policy for the US' take on India's Railway Electrification (CORE).
Implement sustainable aviation fuel (SAF)	**Temporal**: The Department of Energy projects that SAF production will reach 3 billion gallons per year by 2030 which will cover 10% of all domestic aviation. By 2050, it projects that we will produce 36 billion gallons per year which will be enough to fuel the entire industry. **Technology**: SAF is a direct substitute for jet fuel, planes don't require any upgrades. **Deployment-limiting:** We assume that our policy promotes the use of SAF adequately, ensuring that we use as much SAF as is produced in any given year **Policy**: CORSIA and RSF (from above)
Increase Aviation average stock engine efficiency	**Temporal**: Based on recent historical advancements, it is assumed that aviation technology efficiency will increase by 1.5% year over year. Aviation Benefits Beyond Borders reported that efficiency was growing 2.3% annually, but the trend was on a small decline in recent years so we limited this to 1.5%. **Technology**: This gain was applied directly to the sector's stock average efficiency (gal/ton-mile) using compound annual growth rate. **Deployment-limiting:** N/A **Policy**: CORSIA emission requirements serve as incentive for progress.
Electrify short distance aviation freight (< 200 miles)	**Temporal**: There are no plans or reports that we found to project electrification of short flights, so our adoption of this technology is introduced steadily beginning in 2030. Eventually, we projected that electrification will account for 14% of all flights, which is based on the portion of flights that travel less than 250 miles. **Technology**: The impacts of electric aviation were calculated using the Pyka Pelican, a remotely operated small freight aircraft. The Pelican is equipped with 50 kWh of battery storage, which can carry 400 pounds of freight on a 200 mile trip. This aircraft has a fuel intensity of 1.25 kWh/ton-mile. **Deployment-limiting:** We assume that these technologies will develop over time to better meet the needs of the industry. It would be unreasonable to assume we have 100,000 of these flying around instead of far fewer that are eventually capable of taking more cargo. **Policy**: A ban will be placed on non-electric shipping flights under 250 miles .
Small-fleet shipping electrification	**Temporal**: There is no projection for how quickly this project could be deployed, but there are about 1000 ships that can be retrofitted with an electric engine. Our scenario deploys 100-200 of these engines every five years where the more imminent time intervals receive slower adoption.

Freight Transport

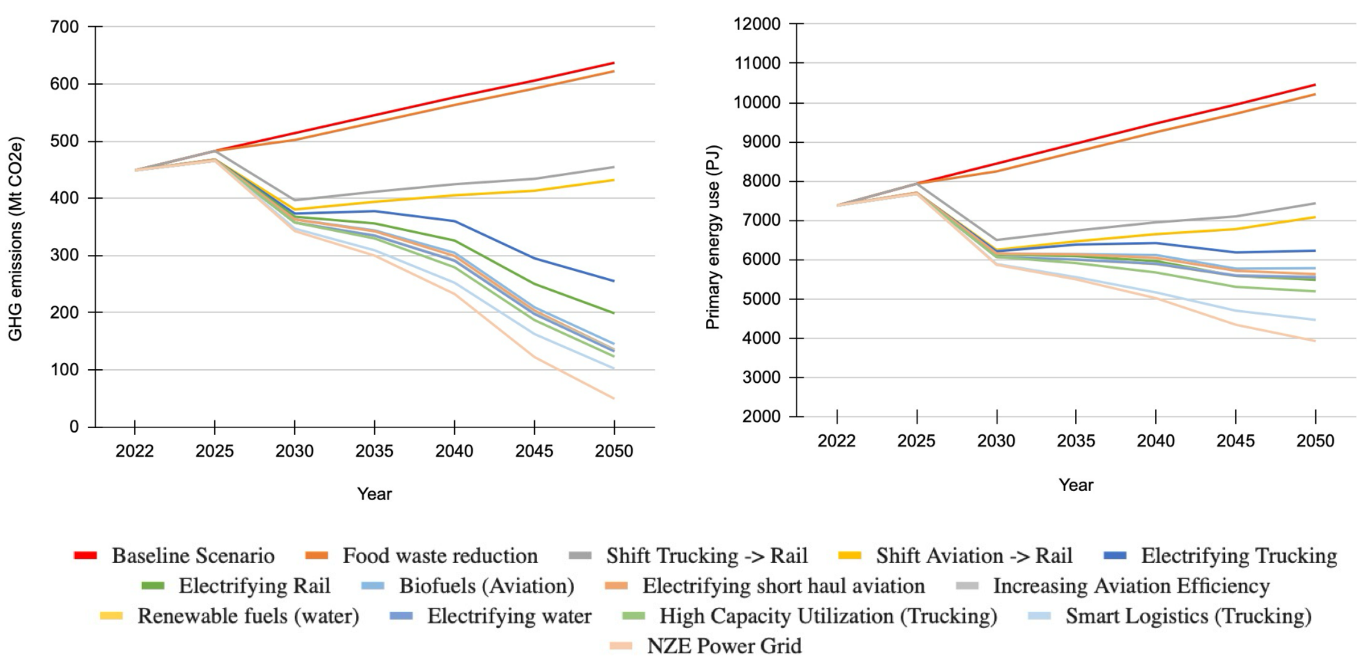
Daniela Rivera Mirabal, Austin Sonnier, Henry Strecker

	Technology: The American Bureau of Shipping outlined that approximately 41 kW were required to match the output of a gallon of diesel. Their designs equipped boats with the equivalent of 150 gallons of diesel, or 5677 kW. This means that the average fuel efficiency for these boats would be 0.056 kWh/ton-mile. **Deployment-limiting:** The average lifespan of the engines on these vessels is about 25 years, our plan may be pushing the transition at a faster rate than these engines would normally be decommissioned. **Policy**: We would seek to utilize the framework of the Electric or Low-Emitting Ferry Pilot Program to incentivize the adoption of electrification in fleet boats.
Ammonia and renewable fuels for water	**Temporal**: The American Bureau of Shipping released a report on the use of biofuels as marine fuel in which they have a figure with projections for the composition of marine fuel use from 2025-2050. This model acts as the framework we based our adoption of ammonia on. We modeled 3% in 2030, 15% in 2040, and 30% in 2050. **Technology**: About 2.5 times more ammonia is required than diesel due to its low energy density, but according to the European Maritime Safety Agency, it pollutes 6.5 times less than marine diesel. **Deployment-limiting:** This technology requires new engines and ammonia storage infrastructure to be implemented. This has spatial implications on where these ships can operate/refuel when this transition is in its early stages. **Policy**: The Electric or Low-Emitting Ferry Pilot Program would support adoption and implementation.

Results

Our Low Energy and Emissions Scenario allowed us to reduce primary energy demand by 2050 from 10,458PJ to 3,439PJ (67% reduction from the baseline scenario). Moreover, the 2050 Greenhouse Gas (GHG) emissions were reduced from 637 to 46 Mt CO_2 by 2050 (92.7% reduction from the baseline scenario). These reductions are a product of over 12 different modeling scenarios, as depicted in Figure 4. In this section, we will describe what strategies were most important for our scenario, and how we could achieve more aggressive reductions.

Figure 4: LEES Freight Scenario



Freight Transport

Daniela Rivera Mirabal, Austin Sonnier, Henry Strecker

We began our analysis by implementing the food waste reduction strategy, which reduced both energy and GHG emissions by 2%. After, we implemented our biggest reduction strategy: shifting ton-miles from trucking to railing. Thanks to our policy banning truck shipments over 1,000 miles (and taxing those from 500-1,000 miles), we were able to shift over 40% of truck ton-miles to rail by 2050. Rail is a very energy efficient transport mode, allowing this strategy to reduce both energy requirement and GHG emissions by approximately 25%. There is a sharp inflection point in this strategy, due to our ban starting in 2030 (as we are not implementing a transition plan beforehand; therefore, there is a sharp increase in trucking ton-mile shipment from 2022-2025 and drastic drop from 2025-2030). From 2030-2050 we shift a higher percentage of truck ton-miles to rail, but the overall increase in shipping demand leads to an overall increase in energy requirement and emissions by 2050 compared to 2030. To this shipment shifting strategy, we also incorporated shifting aviation freight over 2000 miles to rail (which accounts for 20% of aviation's ton-miles). Both shifting strategies resulted in approximately 30% reductions from the initial food waste reduction strategy. For conciseness in this report, we will refer to the "new shipping strategy" as the strategy that incorporates both aviation and trucking shipment to rail, and the food waste reduction strategy.

To reduce the energy requirement and GHG emissions of the new shipping strategy, we must electrify our freight fleet. We first electrified the trucking fleet, as it is the sector with largest energy requirements and GHG emissions. Our scenario assumes 80% of the trucking fleet (both medium and heavy trucks) can be electrified by 2050, reducing the GHG emissions of the new shipping strategy by 40% (and reducing the energy requirement by 12%). We also incorporate the electrification of the rail fleet (97% by 2050), which reduces the GHG emissions of the shifted shipment strategy by an additional 20% and reduces the energy requirement by an additional 10%.

Aviation is the second largest GHG emitting sector. It is harder to electrify the fleet completely, so we started our LEES by switching traditional jet fuel to sustainable aviation fuel (SAF) (100% implementation by 2050). SAF has a higher primary energy than traditional jet fuel, which lends itself to be more efficient when substituted in the same engines that used to rely on jet fuels. This shift in fuel reduces primary energy very minimally, but just enough to outweigh the overall increase in demand. Nevertheless, SAFs lower the GHG emissions by 27%, for which we strongly recommend implementing this strategy. We also implemented electrification of short haul aviation freight (14% by 2050) and increasing the aviation average stock efficiency. These three aviation strategies led to a decrease in GHG emissions of 30% (from the new shipment strategy with electrified trucking and rail) and maintained constant energy requirements (electrification of the short haul flights and increased aviation efficiency reduced the need for some SAF). We also electrified some water fleet (20% by 2050) and changed their fuel source from diesel to more sustainable fuels (biodiesel and ammonia). However, due to the baseline high energy efficiency of inland water, this strategy does not significantly impact the GHG emissions or the energy requirement.

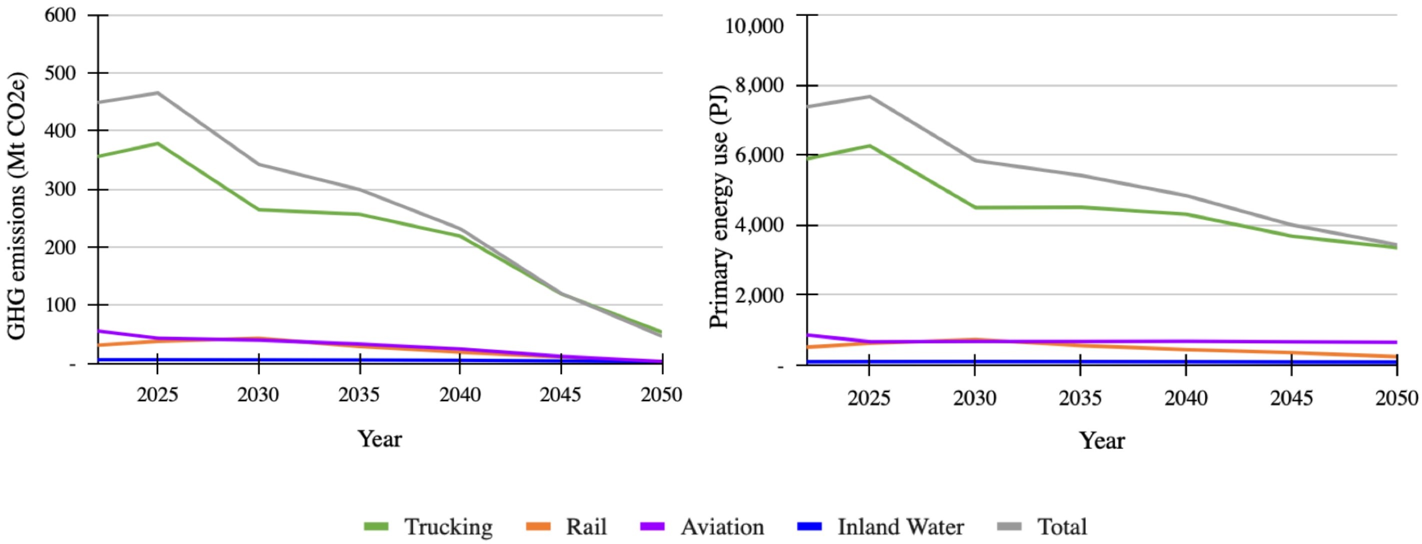
Our current scenario has reduced ton-mile demand by reducing food waste and shifting ton-miles from high emitting sectors to highly energy efficient ones. Moreover, we have transitioned our fleets to mostly electric vehicles (or shifted from petroleum based fuels to sustainable fuels). To further reduce GHG emissions and energy requirements, we must focus our efforts on trucking, as it is still the highest emitting sector. We implement high capacity utilization and smart logistics on the trucking fleet to reduce their emissions by over 20% by 2050. These strategies, coupled with all the previously mentioned ones, reduce GHG emissions by over 80% by 2050 and energy requirements by over 50%, when compared to the baseline scenario. We can implement one more layer to our model to assume we have a low-carbon energy grid. As most of our fleet is now electrified, this grid allows our final reductions to be 93% reductions for GHG emissions and 67% for the energy requirement by 2050.

Figure 5 shows how all freight sectors decreased their GHG emissions by 2050, and how the big reduction driver was the trucking fleet. The primary energy of aviation increases after 2030 due to SAFs, but its GHG emissions greatly decrease, especially when compared to the baseline emissions.

Freight Transport

Daniela Rivera Mirabal, Austin Sonnier, Henry Strecker

Figure 5: LEES Freight Scenario (per sector)



As demonstrated in Figure 4, our most important strategy was shifting trucking ton-miles to rail and electrifying trucking. In our scenario we were unable to reach carbon neutrality by 2050, but we believe this could be done with more aggressive policies in place. If we were able to reduce the overall ton-miles of shipping, we could more easily focus the electrification efforts on a smaller fleet of trucks and electrify it completely. We could also be more aggressive with limiting the amount of ton-miles shipped via aviation (or limiting these to only short haul electrified flights). Both of these strategies would allow our model to reach carbon neutrality by 2050.

Freight Transport

Daniela Rivera Mirabal, Austin Sonnier, Henry Strecker

Reflections

- Challenges with the battery industry:
    - Environmental justice: The production of batteries for BEVs requires large amounts of scarce metals such as lithium, cobalt, nickel, and copper, which are mostly mined in developing countries with weak environmental and labor regulations. This exposes local communities to toxic pollution, water scarcity, land degradation, and human rights violations. Moreover, the benefits of BEVs are mostly enjoyed by wealthy consumers in developed countries, while the costs are borne by marginalized populations in resource-rich regions
    - Mining: Mining poses risks of ecological damage, biodiversity loss, and social conflict, especially in areas with high conservation value or indigenous land claims.
- Hydrogen
    - Hydrogen infrastructure network: Hydrogen vehicles require a network of refueling stations, pipelines, storage tanks and delivery trucks, which are costly and complex to build and operate. Hydrogen also poses safety risks due to its high flammability and potential to cause metal embrittlement.
    - Green hydrogen versus fossil fuel based hydrogen fuel: Most of the hydrogen produced today is derived from fossil fuels, such as natural gas or coal, which emit large amounts of carbon dioxide and other pollutants. Green hydrogen, which is made using renewable energy sources, such as wind or solar, is more environmentally friendly, but also more expensive and less available456. To decarbonize the hydrogen sector, it is essential to increase the production and use of green hydrogen and reduce the reliance on fossil fuel based hydrogen fuel
- Job displacement and demographic makeup of truck drivers
    - The insurance journal report titled "4 Million Driving Jobs at Risk from Autonomous Vehicles" suggests that autonomous trucking could reduce the demand for truck drivers by up to 50% by 2030, leading to job displacement and unemployment for many workers (Simpson, 2017).
    - On the other hand, autonomous trucking could address the current labor shortage in the trucking industry, which is expected to reach 160,000 drivers by 2030. Autonomous trucking could also create new opportunities for truck drivers, such as supervising, maintaining, and operating autonomous trucks, as well as handling the first and last miles of the routes (Collie, 2022).
- Electrifying rail
    - There are no scenarios for transitioning the diesel locomotive fleet to battery-electric or with catenary lines. Therefore, we had to set our own assumptions on how quickly we could change the stock.
    - There is no public dataset for the age of all the locomotives in the US. We found one graph online and had to estimate the values (Vantuono 2022). With more time, we would find a more accurate database to do a more thorough stock turnover analysis.
- Electrifying aviation
    - Our model utilized today's technology to model electric flights into the far future. Although it may be difficult to project how this sector may develop, it would inform our model to be more accurate.

Freight Transport

Daniela Rivera Mirabal, Austin Sonnier, Henry Strecker

References

"Advanced Clean Trucks Fact Sheet | California Air Resources Board." 2021. California Air Resources Board. https://ww2.arb.ca.gov/resources/fact-sheets/advanced-clean-trucks-fact-sheet.

"Ammonia." n.d. Claverton Energy Group. Accessed December 11, 2023. https://claverton-energy.com/cms4/wp-content/files/Ammonia_as_H2_carrier1.pdf.

Albatayneh, Aiman. "Comparison of the Overall Energy Efficiency for Internal Combustion Engine Vehicles and Electric Vehicles." RTU Journal on Economics and Business Management 1, no. 18 (2020): 54-69. https://doi.org/10.2478/rtuect-2020-0041.

"Biofuels as Marine Fuel." 2021. Eagle.org. https://ww2.eagle.org/content/dam/eagle/publications/whitepapers/biofuels-as-marine-fuel-whitepaper-21089.pdf.

Blaze, Jim. 2020. "Commentary: Does rebuilding locomotives beat buying new?" FreightWaves. https://www.freightwaves.com/news/commentary-is-rebuilding-locomotives-better-than-buying-new.

Collie, Brian, et al. "Mapping the Future of Autonomous Trucking." Boston Consulting Group. February 22, 2022

DeAngeli, Emma, Nafisa Lohawala, and Beia Spiller. 2023. "Zero-Emission Trucks and the Inflation Reduction Act: New Loans and Grants for Medium- and Heavy-Duty Electric Vehicles." Resources Magazine. https://www.resources.org/special-series-electrifying-large-vehicles/zero-emission-trucks-and-the-inflation-reduction-act-new-loans-and-grants-for-medium-and-heavy-duty-electric-vehicles/.

Federal Transit Administration, Electric or Low-Emitting Ferry Pilot Program - IIJA § 71102 (Washington, DC: U.S. Department of Transportation, 2023)

Federal Highway Administration. "Compilation of Existing State Truck Size and Weight Limit Laws." Report to Congress, U.S. Department of Transportation, June 2015

"Food Waste FAQs." n.d. USDA. Accessed December 2, 2023. https://www.usda.gov/foodlossandwaste/faqs.

Freight Transport

Daniela Rivera Mirabal, Austin Sonnier, Henry Strecker

"Freight Rail Investments - AAR." n.d. Association of American Railroads. Accessed December 1, 2023. https://www.aar.org/issue/freight-rail-investments.

"Freight Rail Overview | FRA." 2020. Federal Railroad Administration. https://railroads.dot.gov/rail-network-development/freight-rail-overview.

"Fuel Charge Rates." n.d. Canada.ca. Accessed December 7, 2023. https://www.canada.ca/en/revenue-agency/services/forms-publications/publications/fcrates/fuel-charge-rates.html.

"Geographic Area Series: Shipment Characteristics by NAICS by Mode by Distance Shipped for the United States: 2017." 2023. United State Census Bureau. https://data.census.gov/table/CFSAREA2017.CF1700A22?q=cf1700a22&hidePreview=true.

Houser, Kristin. 2023. "World's largest electric cargo plane is unveiled, with payload up to 400 pounds." Freethink. https://www.freethink.com/transportation/electric-cargo-plane.

International Civil Aviation Organization, "Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA)," ICAO, accessed December 10, 2023

Jain, Smriti. 2018. "Indian Railways creates history! Converts diesel loco to 'Make in India' electric locomotive; watch video." The Financial Express. https://www.financialexpress.com/business/railways-indian-railways-creates-history-converts-diesel-loco-to-make-in-india-10000-hp-electric-locomotive-1086123/.

Julin, Kiran. 2021. "Big Batteries on Wheels Can Deliver Zero-Emissions Rail While Securing the Grid." Berkeley Lab News Center. https://newscenter.lbl.gov/2021/11/23/big-batteries-on-wheels-can-deliver-zero-emissions-rail-while-securing-the-grid/.

Freight Transport

Daniela Rivera Mirabal, Austin Sonnier, Henry Strecker

"Latest News - Potential of Ammonia as Fuel in Shipping [updated] - EMSA - European Maritime Safety Agency." 2023. EMSA. https://emsa.europa.eu/newsroom/latest-news/item/4833-potential-of-ammonia-as-fuel-in-shipping.html.

Lattanzio, Richard K. "Heavy-Duty Vehicles, Air Pollution, and Climate Change." CRS Report IF12043. Congressional Research Service, February 14, 2023. https://crsreports.congress.gov/product/pdf/IF/IF12043.

Ledna, C, et al. (2022). "Decarbonizing Medium- & Heavy-Duty on-Road Vehicles: ZERO-Emission Vehicles Cost Analysis", NREL https://doi.org/10.2172/1854583.

Ministry of Railways, "Vision 2024: Indian Railways Electrification Mission" (New Delhi: Ministry of Railways, 2020).

Ministry of Oceans and Fisheries, "2030 Greenship-K Promotion Strategy" to Dominate the Global Green Ship Market (Sejong: Ministry of Oceans and Fisheries, 2020)

"Moving Goods in the United States." n.d. BTS Data Inventory. Accessed December 10, 2023. https://data.bts.gov/stories/s/Moving-Goods-in-the-United-States/bcyt-rqmu/.

"New agreements on urban deliveries without CO2 emission." 2021. Government.nl. https://www.government.nl/latest/news/2021/02/11/new-agreements-on-urban-deliveries-without-co2-emission.

Nunno, Richard. 2018. "Electrification of U.S. Railways: Pie in the Sky, or Realistic Goal? | Article | EESI." Environmental and Energy Study Institute. https://www.eesi.org/articles/view/electrification-of-u.s.-railways-pie-in-the-sky-or-realistic-goal.

Popovich, Natalie, Deepak Rajagopal, Elif Tasar, and Amol Phadke. 2021. "Economic, environmental and grid-resilience benefits of converting diesel trains to battery-electric." *Nature Energy*, no. 6 (November), 1017–1025. https://doi.org/10.1038/s41560-021-00915-5.

Santana, Rafael. 2021. "Decarbonization of U.S. Inland Waterways." Eagle.org. https://ww2.eagle.org/content/dam/eagle/publications/reference-report/decarbonization-of-the-inland-waterway-sector-in-the-united-states-september-2021.pdf.

Freight Transport

Daniela Rivera Mirabal, Austin Sonnier, Henry Strecker

Simpson, Andrew. “4 Million Driving Jobs at Risk from Autonomous Vehicles: Report.” Insurance Journal. March 27, 2017.

“Sustainable Aviation Fuel Grand Challenge.” n.d. Department of Energy. Accessed December 11, 2023. https://www.energy.gov/eere/bioenergy/sustainable-aviation-fuel-grand-challenge.

“Tracking Aviation Efficiency.” 2019. Aviation Benefits Beyond Borders. https://aviationbenefits.org/media/166506/fact-sheet_3_tracking-aviation-efficiency.pdf.

United States Census Bureau. 2023. “….” ECNSVY Commodity Flow Survey Commodity Flow Survey Geographic Area Data. https://data.census.gov/table/CFSAREA2017.CF1700A22?q=cf1700a22&hidePreview=true.

United States Energy Information Administration, Annual Energy Outlook 2020 (Washington, DC: U.S. Department of Energy, 2020)

United States Department of Energy. “Advanced Technology Vehicles Manufacturing Loan Program.” Accessed December 10, 2023.

Vantuono, William C. 2022. “Railinc Locomotive Report: Economic Mirror.” Railway Age. https://www.railwayage.com/mechanical/locomotives/railinc-locomotive-report-economic-mirror/.

Walker, Samuel C. 2013. “Electrification Clearance for Double Stack Container Freight Trains.” Pennsylvania HSR. http://testplant.blogspot.com/2013/09/electrification-clearance-for-double.html.

Wappelhorst, Sandra, and Hongyang Cui. 2020. “Growing momentum: Global overview of government targets for phasing out sales of new internal combustion engine vehicles.” International Council on Clean Transportation. https://theicct.org/growing-momentum-global-overview-of-government-targets-for-phasing-out-sales-of-new-internal-combustion-engine-vehicles/.

“Zero-Emission Vehicle Program | California Air Resources Board.” n.d. California Air Resources Board. Accessed December 5, 2023. https://ww2.arb.ca.gov/our-work/programs/zero-emission-vehicle-program/about.

Zhou, T. 2017. “Life cycle GHG emissions and lifetime costs of medium-duty diesel and battery electric trucks in Toronto, Canada” Transp. Res. Part D 55, 91–98. https://doi.org/10.1016/j.trd.2017.06.019.