ACHIEVING FREIGHT TRANSPORT GHG EMISSIONS REDUCTIONS THROUGH EMERGING TECHNOLOGIES

Avi Mersky and Therese Langer

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Working Paper

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About ACEEE

The **American Council for an Energy-Efficient Economy** (ACEEE), a nonprofit research organization, develops policies to reduce energy waste and combat climate change. Its independent analysis advances investments, programs, and behaviors that use energy more effectively and help build an equitable clean energy future.

About the Authors

Avi Mersky is a senior researcher in ACEEE's transportation program. Avi's research focuses on the policy and regulatory implications of technological changes in transportation, including vehicle automation and electrification. His work has investigated decision making under uncertain technological development paths and maximizing social value, including minimizing environmental risk. He coordinated research for Native American and Tribal Government transportation issues as the research coordinator for the Transportation Research Board Native American Issues in Transportation Committee. Avi holds a PhD in civil and environmental engineering from Carnegie Mellon University, a BS in civil engineering and a BA in international studies, both from Lafayette College.

Therese Langer is a senior fellow in ACEEE's transportation program. Therese Langer works to improve the efficiency of both vehicles and systems for the movement of passengers and freight. Her current areas of focus include technologies and policies to improve vehicle fuel efficiency, digitalization of goods movement to reduce emissions, and sustainable urban freight systems. She was director of ACEEE's transportation program from 2001 to 2020. Therese holds a PhD in mathematics from the University of California, Berkeley.

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Abstract

Freight movement in the United States accounted for 31% of all transportation sector greenhouse gas (GHG) emissions in 2019, and its share continues to grow.[1] This working paper summarizes a preliminary investigation into the potential to reduce freight GHG emissions over the coming decades using emerging technologies that are commercially available today. The focus is on logistical improvements enabled by information and communications technology (ICT), but we include vehicle electrification and vehicle automation and connectivity as well to understand how the emissions reduction benefits of all these technologies may evolve and relate to one another over time.

Our preliminary results show that, in the short and medium term, ICT-based operational improvements, including mode shift, can provide the majority of potential GHG reductions. By 2035 annual GHG emissions for intercity and regional truck freight can be cut by 41%, or 76 million metric tons, from business-as-usual levels, with ICT-enabled reductions representing 55% of the total. By 2050 the ICT share of annual emissions reductions could fall to 30%, as the benefits of electrification will have grown dramatically. ICT would still contribute 43% of cumulative reductions out to 2050 and would also provide benefits from reduced truck volumes and traffic.

The results of this working paper suggest that while vehicle technology improvements such as electrification and automation have great long-term potential for emissions reductions, applying ICT-enabled logistical improvements can achieve substantial emissions reductions in the next 10–15 years, a period in which establishing a rapid trajectory toward eliminating emissions will be essential. In the longer term, both vehicle- and system-based strategies will be necessary.

[1] EPA 2021b. *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2019*. EPA 430-R-21-005. Washington, DC: EPA. www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks-1990-2019.

Introduction

Freight movement in the United States accounted for 30.9% of all transportation sector greenhouse gas (GHG) emissions in 2019, and its share continues to grow (EPA 2021b). Heavy duty vehicles are the source of most freight emissions and a significant portion of transportation emissions as a whole, as summarized in figure 1. This working paper summarizes a preliminary investigation into the potential for emerging technologies to reduce freight GHG emissions. The purpose of the investigation was to better understand the main factors that determine freight emissions, the relationships among these factors, and emissions reductions that could be achieved over time through a variety of technological developments. In particular in this paper, we consider emissions reductions from the use of information and communications technologies (ICT) to improve freight system efficiency, together with improvements to the vehicles themselves through electrification, automation, and connectivity. We seek to understand the relative magnitudes and temporal relationships of the various emissions reduction opportunities and to identify which ICT strategies may warrant a more extensive assessment than what is presented here. The paper also is intended to support the development of a near-term efficiency agenda involving both the freight industry and public policy to achieve substantial carbon reductions in the next 15 years.

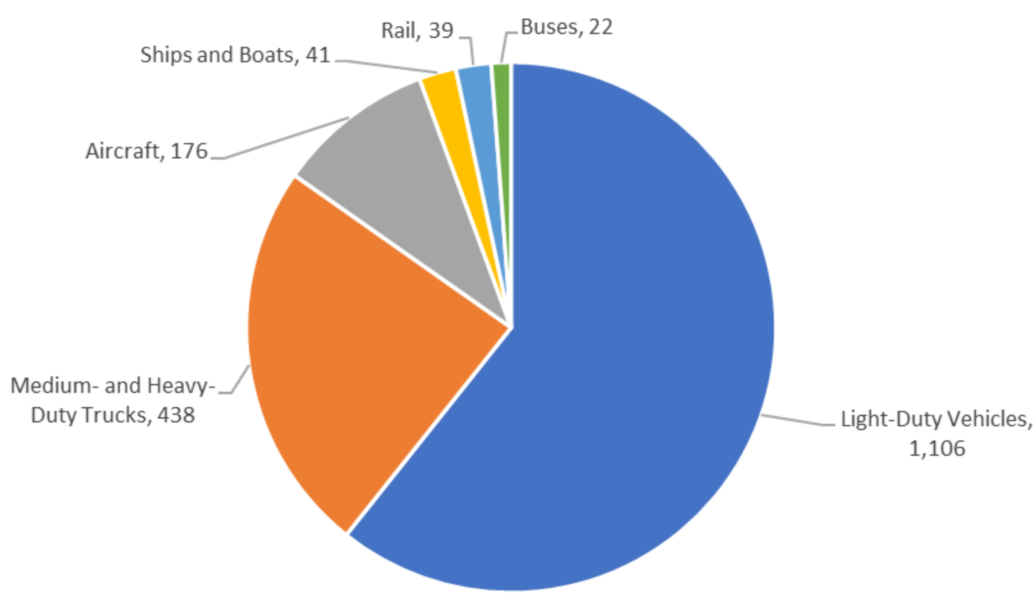

Figure 1. U.S. transportation sector GHG emissions in 2018 by source, million metric tons CO_2 equivalent. Source: EPA 2021a.

Electrification of commercial trucks is rapidly gaining momentum, and success in this endeavor will greatly reduce freight carbon emissions over time, especially with continued decarbonization of the U.S. electric grid. It will take time, however, for electric trucks to replace the diesel fleet, especially in the case of tractor-trailers, which account for nearly two-thirds of all truck energy use (Davis and Boundy 2020). These will not be among the first trucks to be electrified in large numbers. As of July 2021, more than 137,000 electric trucks had been deployed or ordered in the United States; fewer than 10% of those were tractors (EDF 2021). By contrast, connectivity and automation technologies in some cases are likely to be adopted for long-haul tractor-trailers before any other truck types, but here, the lack of a regulatory framework and limited benefit for early adopters mean substantial uptake is many years away.

As these technologies make their way into the fleet, it is important to move quickly to apply them so as to establish a sharp downward trajectory on emissions and limit cumulative carbon in the atmosphere over the coming decades. System efficiency improvements—that is, reductions in energy used per ton-mile[2] of freight delivered—generally can be implemented with the trucks that are already on the road and hence can begin reducing emissions sooner. Moreover, efficiency gains will remain important even as trucks become cleaner. Roadway capacity is already strained and is projected to tighten further, with truck miles expected to increase 53% from 2020 levels by 2050 (EIA 2021).[3] Improving roadway capacity has traditionally been accomplished primarily by increasing freeway lanes; this is an expensive endeavor, and governmental fiscal constraints are likely to continue far into the future. Reducing the number of truck miles required to meet a given freight demand will be key to avoiding worsening congestion and unreliable delivery times. Furthermore, digitalization and ICT strategies are already moving rapidly into the trucking sector, and it is essential that this opportunity be harnessed to reduce carbon emissions as well as to provide economic benefits. Finally, maintaining a reliable surface freight system will help to prevent further shifts to energy-intensive air freight.

[2] *Ton-miles,* in this report, represents the total weight of a load multiplied by the distance from origin to destination. This distance is in contrast to the total distance that the truck must actually travel, which can include indirect routing.

[3] More recent Federal Highway Administration estimates show the possibility of growth of up to 76%. Analysis for this project was completed before these reports were released, and all estimates reflect EIA *Annual Energy Outlook 2021* assumptions.

Technologies and Assumptions

To put the discussion of freight efficiency potential in a quantitative setting, we created a spreadsheet model to represent U.S. freight sector emissions and how they could change with the introduction of new technologies and practices between now and 2035, and between now and 2050, reflecting medium- and long-term impacts, respectively. Our focus is on the medium term, where the time needed to implement the various emissions reduction strategies is especially important. The 2050 projections are very speculative, but we include them to show how the relative contributions of these strategies shift as vehicle fleets turn over.[4] Our analysis aims for computational simplicity and, given the many complexities and unknowns of future freight transportation, is intended to illustrate the relative magnitudes of impacts of various efficiency strategies over time.

This analysis is largely about truck transport, because trucks account for the bulk of freight emissions: 77.5% in 2019 per the Environmental Protection Agency (EPA 2021b). They also have the greatest potential for near-term operational shifts. Our analysis does include truck-to-rail mode shift. Among trucks, we focus on regional and long-haul tractor-trailers and exclude trips of less than 100 miles. With these limitations, the freight truck trips considered here represent about 50% of all truck fuel use.

We only investigate regional and long-haul freight in this report. Urban freight presents a unique set of challenges and opportunities, and many ICT technologies and applications investigated in this report, such as inter-modality, will not apply to intra-urban freight. Moreover, freight movement's direct impacts on urban populations through local pollutant emissions, collisions, congestion and noise have heightened significance in that case and cannot be subordinated to the impacts of carbon emissions. However, most of the strategies for improving efficiency considered here have urban analogues or extensions and may offer comparable or even greater opportunities in terms of percent emissions reductions. Furthermore, the interface between interurban and urban freight movement will ultimately be crucial to successful emissions reductions in both domains. Hence extending this analysis of potential to urban freight, while beyond the scope of this paper, could be a useful exercise.

[4] The analysis considers only technologies that are commercially available today, so our long-term projection of combined potential may be quite conservative.

This section summarizes our assumptions regarding the various emissions reduction approaches considered.

ICT APPLICATIONS

ICT applications to freight efficiency include technologies that use real-time tracking of logistics and transportation assets, as well as freight demand, to better control the deployment of those assets. This represents a combination of multiple technologies and capabilities, such as the tracking of loads, vehicles, freight demand, warehouse capacity, and more. Software can then use this information to optimally assign freight demand to a combination of assets, as well as to determine how to optimally use those assets. ICT applications considered in this report are specifically those that control multiple freight loads and assets concurrently. This excludes technologies to optimize vehicle fuel efficiency.[5] We generally treat connected and automated vehicle (CAV) technologies as a separate category, though these are, technically speaking, ICT enabled as well. And in fact, if a truck is using connectivity to accept real-time information and adjust its routes and freight assignments accordingly, we count that as an ICT application.

ICT-based strategies we consider include those that reduce empty miles, optimize trailer or container loading, assist with trailer and tractor pairing, or help shift freight from truck to rail. These applications were selected because they are already in use to some extent and are expected to grow in use as the technology that enables them becomes cheaper, more available, and more proven and as more logistics service providers adopt them (Mihelic and Roeth 2019). While not a comprehensive list, these applications do address the principal sources of inefficiency in intercity and regional freight movement.[6] Our analysis is intended to assess the potential for additional emissions reductions through the increased ease and efficacy of these freight efficiency strategies enabled by the use of ICT. While intentional pairing of tractors and trailers will lead to direct changes in fuel economy, the other strategies will lead to a change in total miles driven to deliver a given amount of freight demand, represented as ton-miles per mile traveled. This can come from either a direct reduction of miles traveled in a trip or an increase in the fullness of a trailer, decreasing the

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[5] We made an exception for ICT-enabled aerodynamic pairing of tractors and trailers.

[6] Optimizing the configuration of warehousing, distribution, and intermodal facilities is not explicitly addressed by any of the strategies considered here. However, high implementation levels of strategies such as co-loading and route optimization will likely coincide with network optimization.

number of trips necessary to meet freight demand.[7] The following sections describe each of these ICT-enhanced strategies and our key assumptions regarding their use. These assumptions are summarized in table 1.

Reducing Empty Miles

It is not uncommon for trucks to drive empty on the return to their logistical home. Estimates of total empty backhauls, as such trips are called, vary. One recent analysis estimates that 19.5% of all miles are driven empty nationally, while other sources estimate the value as closer to 25% or even 35% (FDOT 2018; Meller, Ellis, and Loftis 2012; Convoy 2021). The percentages vary greatly by fleet and service type (Meller, Ellis, and Loftis 2012). Empty miles are also dictated to some extent by imbalances in regional flow, such as the need for more loaded refrigerated trailers leaving Florida, with its citrus industry, than coming in (FDOT 2018). Our analysis does not explicitly account for such considerations but instead relies on national average performance data to estimate the potential for reducing empty miles.

Many logistical software systems and services can help find loads for backhaul trips to improve capacity utilization. Freight brokers and marketplaces, such as Uber Freight, offer services that pair deliveries with return trips, allowing fleets—especially the smaller ones—to reduce their empty miles (Heilmann 2020). Estimates of the empty miles that can be eliminated in this way vary from 15% up to 46%, depending on carrier type (Kearns, Sze, and O'Rourke 2020; Heilmann 2020; Convoy 2021). We assume a potential reduction of 23% for the fleet as a whole, which is what carriers using Uber Freight's bundling service have achieved (Heilmann 2020). To the extent that these initial estimates are empirically based, they should reflect constraints such as regional flow imbalances.

While we were unable to find estimates of how quickly this technology could be adopted, the rapid growth of a new freight market platform can be illustrative. We used Uber Freight's target market size and revenue growth since launch in 2017 to build an S-curve representing the market penetration of ICT-based trip bundling (Uber 2021a, 2020, 2021b).[8] We applied

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[7] Increased fullness will reduce truck miles per gallon, offsetting to a modest degree the savings from reduced trips, but we have not yet factored that into our analysis.

[8] Uber Freight's market share grew from 0.0094% in 2018, the first full fiscal year of its service, to 0.027% in 2020, based on an estimated $3.8 trillion target market. Uber states that the percentage growth in revenue was approximately equivalent to the percentage growth in shipped weight.

the resulting annual growth rates to all ICT-based efficiency strategies discussed here as a placeholder until we find better estimates. The resultant curve of adoption rate over time can be seen in figure 2.

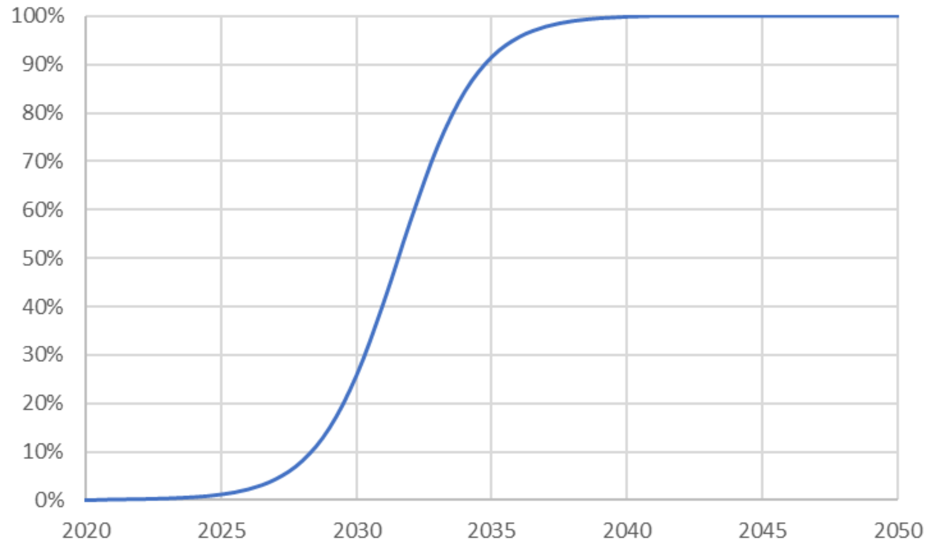

Figure 2. Assumed ICT technology adoption rate by year

Cube Optimization

A single large shipper can improve load factor in some cases by optimizing packing. The amount of freight that a truck can carry is subject to weight and volumetric constraints. Most fully loaded vehicles "cube out" rather than reach their weight limit, due to the nature of goods carried, so space is most often the binding constraint. Under such circumstances, volumetric utilization can often be improved by optimizing the combination and organization of items placed within a trailer or shipping container. Today software tools can use the geometric data of goods being shipped to optimize not only the goods being loaded into one container or truck but also the distribution of such goods among multiple containers. Such applications require dynamic decision making and hence are ICT enabled. Although small players have been less able to use these tools, they have been gaining adoption by large companies, such as Walmart and Home Depot, proving their ability to increase total loading per container. For example, Home Depot has achieved an average fullness of 85% in its fleet, an increase of 13% over the estimated fullness of 75% without the packing software (Façanha et al. 2019).

Cube optimization can be used by truckload (TL) carriers as well as private fleets.[9] Shipments on such fleets account for about 90% of the market (Meller, Ellis, and Loftis 2012). There are, however, limits within these markets. Both private and truckload fleets must have enough demand to fully load their trucks, and the shipped items must be geometrically compatible to be packed more efficiently than the status quo. Certain shipments, like live animals, cannot simply be more optimally stacked on top of each other. At present, we ignore these complications and assume that the full 90% of the trucking market can take advantage of this technique and improve average trailer fullness by about 13%.

We assume the same growth rate for the utilization of packing software as for empty backhaul minimization but apply it to only 90% of the total trucking market.

CO-LOADING

Freight rarely travels directly from its origin to its destination. Instead, it often has to travel through multiple distribution centers to reach its final destination. This is especially true when less-than-truckload (LTL) shipments are combined to fill trucks. These shipments can be loaded and unloaded multiple times along circuitous routes to their final destinations in an attempt to increase trailer space utilization. However, improvements in trailer utilization do not always have to come at the expense of route efficiency. While shippers who want direct routing often pay for a full trailer to ensure this treatment, new companies, enabled by improvements in communication technology, are making it easier to match loads that have origins and destinations along similar routes. These companies take advantage of a combination of constant tracking of their available and in-use trucks, routing software, and automatic task assignment to offer customers the ability to co-load their goods for more direct shipments and to receive real-time quotes and delivery estimates. This method is generally not compatible with cube optimization, as co-loading requires the packing of an individual customer's shipment on pallets, which reduces the ability to optimize the geometry of loading (Flock Freight 2021).

Co-loading is separate from but complementary to backhaul minimization: Instead of reducing the miles driven by unloaded trucks, co-loading works to decrease the distance driven when trucks are loaded or to increase the load factor of a partially loaded truck. Opportunities for co-loading may be limited by commodity incompatibilities, as certain materials cannot be shipped together. Food or medical equipment, for example, may not be

[9] Truckload carriers are third-party fleets that carry shipments from only one customer at a time.

able to share a truck with certain hazardous products. As with empty miles reductions, our analysis avoids these complexities by drawing from empirically based averages that reflect such limitations.

Kearns, Sze, and O'Rourke (2020) cite GHG reductions of up to 30% through co-loading, while one provider, Flock, estimates GHG reductions of up to 40% (Flock Freight 2020). McKinnon (2018) also suggests the possibility of large companies directly collaborating to improve their load factors. The total reduction in GHG emissions will also vary depending on where the freight is diverted from, as co-loading can be used on truckload, less-than-truckload, and private fleets, each of which has different average routing and loading characteristics. Our model includes only the increase in load factor of current less-than-truckload shipments where truck space is shared by two or more customers. This is about 10% of the market (Meller, Ellis, and Loftis 2012).

We assume that these LTL loads can increase to the current industry average for truckload shipments. This would represent a growth in fullness from 35% (LTL average) to 65% (TL average), or an 86% increase in fullness (Meller, Ellis, and Loftis 2012). We assume market share growth equivalent to that of empty backhaul minimization but apply this only to the 10% of the total market that we assume is capable of being shifted in this way. We also assume that any reductions in miles traveled will be captured by the effects of empty backhaul minimization.

This estimate excludes benefits of co-loading more broadly. Because we have assumed that private fleets and TL carriers adopt cube optimization, these fleets were not eligible for co-loading.

Optimal Pairing of Tractor and Trailer

Traditionally tractors and trailers are considered separate assets, with tractors simply pairing with an available trailer at a depot or pickup point (Mihelic and Roeth 2019). Innovative designs of tractors and trailers can improve aerodynamic performance, but for this to happen, trailers must be paired with compatible tractors (Mihelic and Roeth 2019). ICT-enabled improvements in asset management, tracking, and route assignment may allow the growth of intentional pairing of compatible tractors and trailers by making more specially designed trailers available to intentionally paired tractors (Mihelic and Roeth 2019). Fuel economy improvements from such intentional pairing must be at least 6% to justify expenses, and improvements have been demonstrated to be as high as 13.8% with current technology (EPA 2021c; Mihelic and Roeth 2019). We assume that fuel economy gains from intentional pairing will linearly grow between these two values over the first 10 years of our study period.

Unlike other ICT techniques, intentional trailer pairing will achieve major savings only for new vehicles, both trailers and tractors. Adoption is therefore dependent on the growth in sales of physical hardware. The replacement rate of trailers is lower than that of tractors, with each trailer lasting about 12 years (NPTC 2017). This means the availability of aerodynamic trailers is a limiting factor in pairing opportunities. We assume that trailers designed for pairing will increase in market share by 2.7% per year, starting at 0%. This is the rate of increase in sales required for zero-emission vehicle (ZEV) Class 8 tractors by California's Advanced Clean Truck (ACT) rule. We also assume that said market share will be the main limiting factor in intentional trailer pairing. In the absence of specific usage rate data, we further assume that such trailers will initially be paired with intended tractors for 25% of their miles traveled and that this rate will increase by 2% per year, as suitably designed equipment becomes a larger part of the fleet and better utilizes ICT tools to travel on routes where intentional pairing is possible.

Mode Shift

While the preceding strategies are all directed at trucking, there are also opportunities to increase use of rail or waterborne modes, which are more energy efficient than trucking and typically less expensive. Trucking has dominated many freight markets due to its more predictable scheduling, accommodation of small loads, and ability to provide door-to-door service. Today third-party logistics companies are developing and utilizing ICT tools that analyze routes, mode options, costs, and shipping timelines to allocate shipments across the cheapest or most efficient combination of modes to reach their destination within customer-acceptable time frames (Kearns, Sze, and O'Rourke 2020). For example, GE Transportation's Port Optimizer, a cloud-based container data portal designed to advance supply chain integration and enable predictive analytics, will allow trucking operations and railroads, among others, to track and streamline their operations at maritime ports (Cartwright 2019). These tools can make rail or intermodal shipping practical in more situations, including for smaller shipments, shorter distances, and certain specialized goods.

We assume a 1% per year shift in ton-mile demand from trucks to rail through 2030, after which the shift is assumed to be 0.5% per year, as the ICT tools cited for near-term mode shift may encounter diminished opportunities to develop new markets for rail and intermodal. This assumption is conservative in that the increase in rail and intermodal demand should produce new infrastructure investment and lead to greater growth in rail in the medium and long term. As in the case of CAVs, however, this paper highlights the effects of only those advances for which there is a clear path foreseeable today and hence considers only the direct benefits of ICT applications to rail and intermodal.

It should be noted that the ICT-based technologies discussed here and in prior sections will tend to reduce trucking costs and consequently could in fact *increase* truck mode share at the expense of more energy-efficient modes. In a regional study, the U.S. Department of Energy found that cost reductions resulting from higher truck load factor could increase the mode share of trucks by more than 10% at the expense of rail and water shipping, even though the most energy-efficient option would be a 54% shift in truck demand to rail (DOE 2020). In addition, improvements in truck efficiency and truck electrification will tend to reduce the energy efficiency and emissions advantages of rail over truck unless similar advances occur for locomotives. Hence, efforts to increase rail and intermodal mode shares should occur in tandem with improvements in locomotive technology.

ELECTRIFICATION OF TRUCKS

We have based our truck electrification assumptions on California's ACT rule (CARB 2021; Buysse and Sharpe 2020) and the more recent executive order from California's governor mandating a 100% share of electric tractor-trailer sales by 2040 and requiring that all tractor-trailers on the road be electric by 2045, "wherever feasible"[10] (Office of the Governor of the State of California 2020). We assume that electric tractor sales percentages will follow the ACT requirements starting at 5% in 2024 and reaching 10% in 2026, at which point they will increase linearly to 100% by 2040. We have kept the fleet replacement rate, 10 years or 10% per year, unchanged from current conditions until 2036 (EPA and DOT 2016). At that point we set aside the replacement rate and instead assume that the total on-road electric vehicle (EV) share increases linearly to 100% by 2050. This is meant to model an increase in scrappage and turnover to comply with expected mandates applicable to vehicles on the road. This is slightly more conservative than California's target of 100% Class 8 tractors on the road "wherever feasible" by 2045. We use the California Air Resources Board's estimated electric tractor efficiency of 2.1 kWh/mi (CARB 2019).

To calculate the associated CO_2 emissions reductions, our analysis assumes a linear transition of U.S. average grid generation mix from current conditions as described by the EIA (2021)

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[10] We assume that electric tractor sales percentages will follow the ACT requirements, starting at 5% in 2024 and reaching 10% in 2026, at which point they increase linearly to 100% by 2040. We keep the fleet replacement rate unchanged from current conditions until 2036. At that point we ignore the replacement rate, and the total on-road EV share increases linearly to 100% by 2050. This is meant to model an increase in scrappage and turnover to comply with expected mandates applicable to vehicles on the road. This is slightly more conservative than California's target of 100% Class 8 tractors on the road "wherever feasible" by 2045.

to a 5% coal, 39% natural gas, and 57% zero-direct-emissions grid[11] in 2050, as envisioned in Nadel and Ungar (2019).

CONNECTIVITY AND AUTOMATION

Among CAV capabilities, we considered vehicle platooning and road grade preview as representative of CAV features that have already been tested (or eco-driving technologies that have already been road tested). These are provided by technologies such as cooperative adaptive cruise control (CACC) and control optimization systems, which control vehicle velocity to reduce fuel consumption. CACC platoons involve multiple vehicles, at present usually two or three, synchronizing their velocities to improve the performance of following vehicles. Road grade preview allows optimization of velocity to take advantage of upcoming slope changes.

We assume that both technologies will be available in new vehicle purchases and will increase in share of new sales by 2.7% per year, starting with 0% of sales in 2020. This is an aggressive adoption rate given that neither platooning nor road grade preview optimization is expected to be usable on all trips. Road grade preview requires accurate maps, and platoons require other vehicles to pair with. We assume that, for equipped trucks, these technologies will be available on 25% of all trips to start and then increase by 2% per year. We further assume that these technologies can run concurrently and that their effectiveness on a single truck is multiplicative (i.e., the efficiency impacts of the two technologies are independent of each other). We assume that CACC platoons consist of CAV trucks and reduce average emissions by 9.43% (Lu and Shladover 2014). Actual efficiency gains depend on platoon length and truck position in the group (Lu and Shladover 2014). While road grade preview and other eco-cruise-control techniques have differing effects depending on traffic and road topology, we assume average emissions reductions of 2.75% per mile (Vahidi and Sciarretta 2018).

[11] The 57% clean grid is projected to consist of 43% renewable (41% wind, 59% solar) and 14% nuclear.

Table 1. Summary of assumptions regarding strategies

	Assumptions (see text for more detail and sources)
Reduced empty miles	• Trips are either full or empty • Target market share is 100% of the total freight market • Reduction in empty miles of 23% is possible
Cube optimization	• Target market share is 90% of freight market • Cube optimization increases fullness by 13%
Co-loading	• Target market is 10% of freight market • Co-loading increases fullness by 86%, climbing from LTL rate to TL rate
Tractor-trailer pairing	• Sales of pairable systems increase by 2.7% per year • Share of trips for which pairable trailers are paired starts at 25% and increases by 2% per year
Truck-to-rail shift	• Ton-mile demand from truck to rail increases linearly by 1% per year until 2030, then 0.5% per year • Rail packing can benefit from cube optimization equivalent to that of trucks. • Rail vehicle performance and fuel source remain constant.
Electrification	National power grid shifts linearly from 20% coal, 38% natural gas, and 41% zero direct emissions to 5% coal, 39% natural gas, and 57% zero direct emissions by 2050
CAV technologies	• CACC platoons consist of three trucks • Sales grow linearly to 40% by 2040

Results

The strategies discussed above can reduce freight GHG emissions by 1) increasing truck load factor (in ton-miles per mile), 2) reducing truck per-mile emissions rates, or 3) reducing GHG emissions per ton-mile by shifting from truck to rail. We first present results for each of these three mechanisms separately and then compare and combine the three.

In our calculations, total increases in ton-miles delivered per mile traveled, achieved through ICT-based strategies, are 24% by 2035 and 27% by 2050. Gains are greatest from cube optimization, at 12% by 2035 and 13% by 2050 (figure 3). The shape of the curve is similar for all ICT strategies due to our application of the same adoption curve for all three. Some technologies may be easier to adopt, but we were unable to find any specific data on feasible adoption rates to allow us to model them separately.

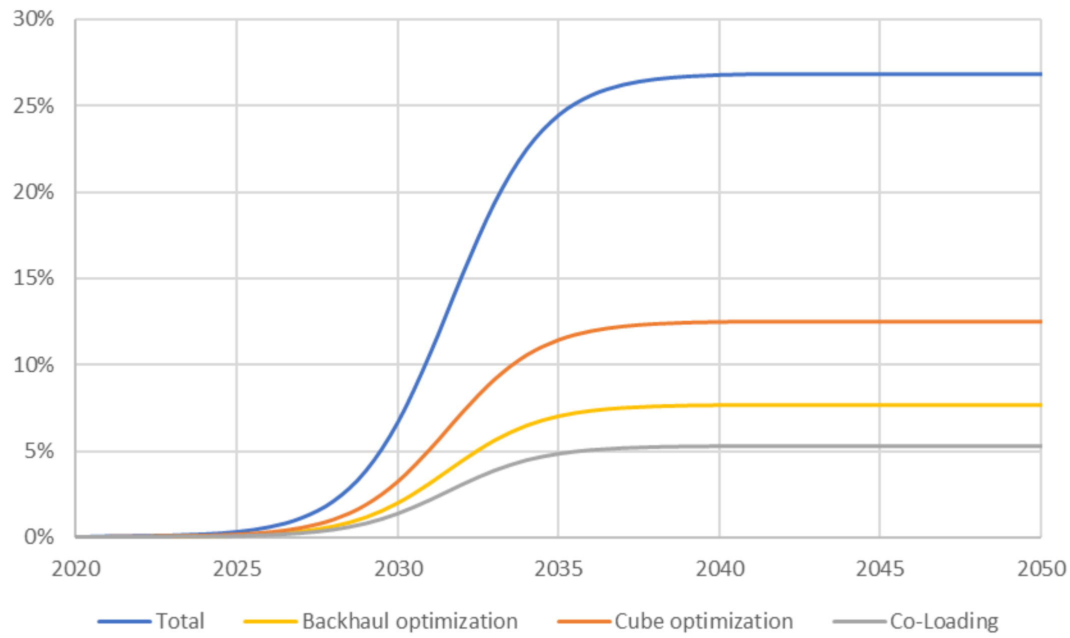

Figure 3. Percentage change in ton-miles per VMT achievable by load factor strategies

Among strategies that affect truck GHG emissions rates (figure 4), truck electrification yields an 18% reduction by 2030 and 66% by 2050, dominating the reductions from truck technology strategies.[12] Electric trucks' very large GHG reductions over time are due to the combination of electric powertrains' high efficiency and assumed steady gains in decarbonizing the electric grid on average across the United States.

[12] The EPA's and U.S. Department of Transportation's Phase 2 heavy-duty vehicle GHG standards will enforce some truck efficiency improvements over this time frame, but we do not include these gains at this stage. Our vehicle improvement investigations focused on non-regulation-mandated or assumed factors, though Phase 2 improvements may decrease the space of potential gains. For our purposes, *vehicle improvements* included trailer pairing, which Phase 2 regulations assume are unlikely without significant ICT investment.

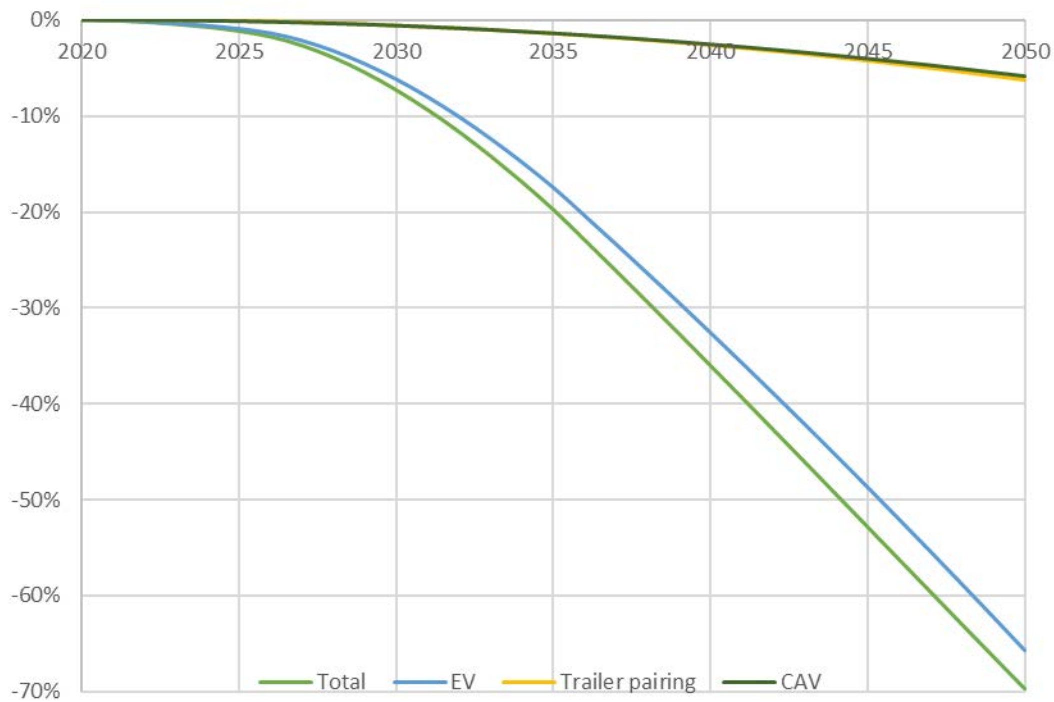

Figure 4. Percentage change in GHG emissions per mile (not including mode shift to and from trucking)

For mode shift, GHG emissions reductions are driven by the difference between the emissions rates of truck and rail transport over time, as shown in figure 5. Since the only improvement to rail efficiency that we model comes from cube optimization, rail's emissions advantage over trucks decreases as trucks become cleaner. If the trend lines continued past the study period, trucks would eventually have lower emissions per ton-mile than rail.[13]

Major rail efficiency improvements and emissions reductions over the next 30 years are possible, such as through electrification. Such improvements could preserve the GHG emissions advantage of the rail mode even with the arrival of electric trucks. At present, some in the freight rail community are skeptical of the feasibility of track electrification, but electric locomotives running on batteries or fuel cells are under development (AAR 2021b, 2021a).

[13] The analysis ignores most ongoing incremental improvements in both rail and truck efficiency, accounting only for the technology advances discussed in this paper (electrification, CAV technologies, and ICT-based efficiency improvements).

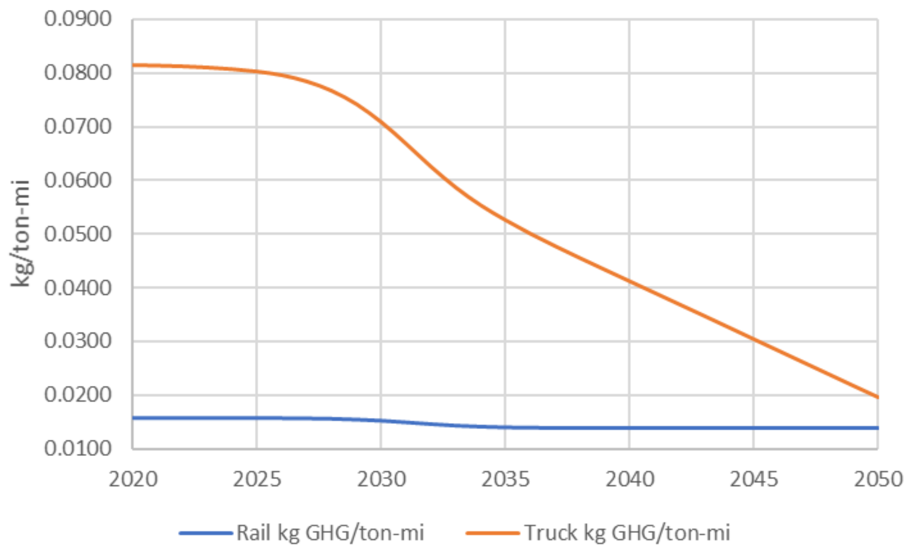

Figure 5. GHG emissions rates for truck versus rail

Given our assumptions regarding truck and rail technology adoption, the assumed shift from truck to rail reduces average freight emissions rates by about 5 grams per ton-mile by 2030, but this benefit declines to around 1 gram per ton-mile by 2050.

Comparing and Combining Savings From Emissions Reduction Mechanisms

Under our assumptions, ICT-based operational improvements (including mode shift) provide the majority of potential GHG reductions in the near and medium terms. ICT improvements reduce annual GHG emissions more than CAV and EV technologies together through 2037, (figure 6) and they reduce cumulative GHG emissions more than CAV plus EV through 2043 (figure 7). This is largely because ICT improvements, such as better packing techniques and reduction of empty miles, can take effect for vehicles already on the road, while vehicle efficiency gains and electrification generally apply to new vehicles only. If accelerated fleet replacement were possible, then vehicle energy efficiency improvements could dominate emissions reductions sooner. It is also notable that ICT gains begin leveling off around 2035. This is because market share begins leveling off as the technologies reach market saturation. Over the long term there may be further improvements in efficiency possible from ICT, but this analysis considers only gains that can be demonstrated from existing technologies and use cases.

Also, there are synergies between ICT and electrification. For example, one of the greatest barriers to the adoption of electric trucks in the near term is route limitations associated with charging infrastructure. ICT can help ensure that trucks can be charged during planned idle times and reach full utilization.

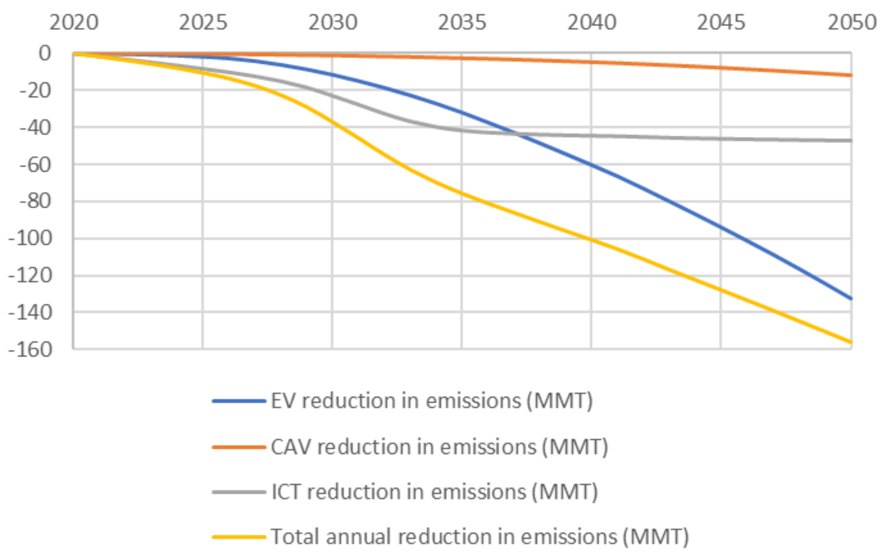

Figure 6. Annual GHG reductions by technology type

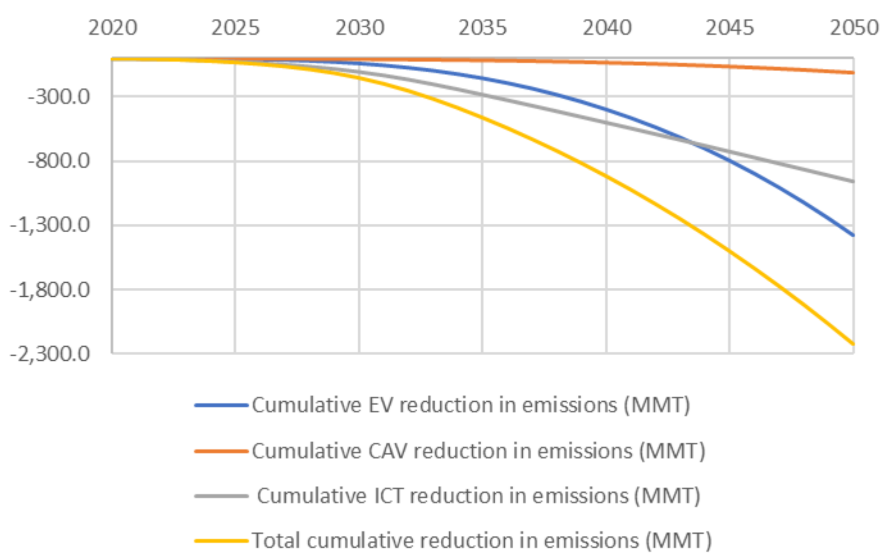

Figure 7. Cumulative GHG reductions by technology type

To estimate the combined effects of all emissions reduction mechanisms, we assume the emissions reductions or efficiency gains for the various technology groups are independent of one another.[14] In that case, the combined percentage reduction can be calculated by

[14] In reality, CAV technologies are expected to be less effective, on a percentage energy savings basis, in electric vehicles, but this is not reflected in our analysis. There are other cases in which strategies are not independent

multiplying together the effects of the individual technology groups. To convert the resulting percentage reduction to tons of GHG emissions, we begin with EIA projections of total truck freight emissions (EIA 2021).[15] We then reduce this to account for 1) tractor-trailer share of freight truck fuel use and 2) the share of truck ton-miles in trips greater than 100 miles, since this analysis is about intercity and regional freight only (Davis and Boundy 2020).[16] Our preliminary results suggest that annual GHG emissions from intercity and regional trucks can be reduced by 41% (76 million metric tons) in 2035 and 77% (160 million metric tons) in 2050 by all strategies combined, relative to EIA projections for those years (EIA 2021). Of these reductions, ICT accounts for 55% in 2035 and 30% in 2050. ICT's share of cumulative reductions is higher, at 62% of 460 million metric tons of total avoided emissions in 2035, and 43% of 2,200 million metric tons of total avoided emissions in 2050.

Next Steps

Our next step will be to take a closer look at both the effectiveness and the feasibility of the potential ICT-based reductions we have identified. Using additional examples of early applications of ICT in freight transport, we will specify how these strategies deliver operational efficiencies in enough detail to improve our estimates of the likely benefit to adopters as well as the size of the market and rate of adoption out to 2035. Future models may also capture the effects of the uncertainty in our model inputs and assumptions, either through scenarios or Monte Carlo analyses.

We will look further into the relationships between ICT-enabled system efficiency improvements and vehicle automation and electrification. We will also explore costs and benefits, beyond fuel savings and emissions reduction, associated with adoption of ICT tools, including impacts on shipment times and reliability. It is true that tons of emissions reduced from system efficiency will decline as vehicles become dramatically cleaner in the longer term; however, continued proliferation of heavy-duty vehicles and truck miles traveled will have other adverse impacts including congestion and inefficient land use regardless of their

(e.g., co-loading and cube optimization), but we have corrected for those directly in our estimates of individual strategy benefits.

[15] See table 19, "Energy-Related Carbon Dioxide Emissions by End Use: Case: Reference Case."

[16] See tables 5.1, 5.2, and 5.19.

per-mile emissions. Thus, system efficiency strategies will remain crucial to the sustainability of freight transport and hence to economic health.

Ultimately, the value of this sketch analysis lies in its ability to point the way toward investments, behaviors, and policies that will help ensure that the ongoing growth in ICT applications in freight will substantially reduce the carbon footprint of freight transportation, beginning in the next few years. Questions to be addressed next may include:

- How is ongoing deployment of ICT tools in the freight industry affecting emissions today, and how can the outcomes be improved?
- What market-based measures can accelerate the application of ICT tools to reduce emissions?
- How can the availability of real-time data be used to help drive behavioral shifts toward lower-emissions freight options?
- What kinds of public investments (e.g., data sharing platforms, urban consolidation centers) would be most helpful to advance ICT-based emissions reductions?

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