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Policy Analysis

Health and Climate Impacts from Long-Haul Truck Electrification

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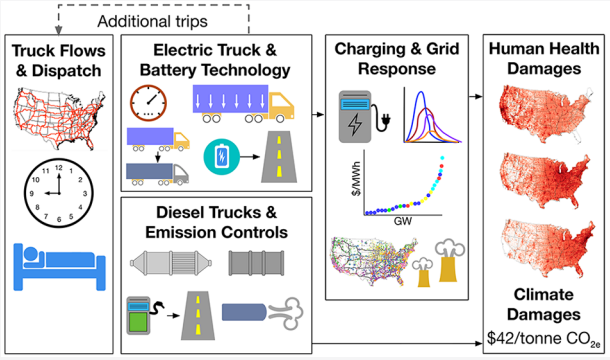
ABSTRACT: Long-haul truck electrification has attracted nascent policy support, but the potential health and climate impacts remain uncertain. Here, we developed an integrated assessment approach with high spatial-temporal (km and hourly) resolution to characterize the causal chain from truck operation to charging loads, electricity grid response, changes in emissions and atmospheric concentrations, and the resulting health and climate impacts across the United States. Compared to future diesel trucks, electrified trucking's net health benefits are concentrated only along the West Coast with a business-as-usual electricity grid. However, with an 80%-renewable electricity grid, most regions would experience net health benefits, and the economic value of avoided climate and health damages exceeds $5 billion annually, an 80% reduction relative to future diesel trucks. Electric trucks with larger batteries may increase health and climate impacts due to additional trips needed to compensate for the payload penalty, but a 2× improvement in the battery specific energy (to ∼320 Wh/kg) could eliminate the additional trips.



KEYWORDS: *Human Health, Climate Change, Freight, Battery-Electric Trucks, Air Pollution, Social Costs*

■ INTRODUCTION

Trucks form the backbone of the freight system in the United States—they haul 71% of total United States (U.S.) freight by payload, 73% by value, and 42% by payload weight-distance.[1] The trucking sector in the U.S. employs 2 million drivers, and that number has been growing at 5% per year.[2] Even though heavy-duty trucks (i.e., Class 7 and Class 8 trucks) represent only 1% of on-road vehicles, heavy-duty trucks account for 28% of U.S. on-road vehicles' energy consumption, 27% of on-road greenhouse gas emissions, and 47% of on-road vehicle NO_x emissions.[1] Compared to light-duty vehicles, freight trucks consume far more energy per vehicle due to the high-power and heavy-load duty cycle.[3] This low vehicle-level fuel economy combined with their intensive use (>100,000 km per vehicle annually) translates into significant fleet-wide energy consumption and tailpipe emissions, which are expected to continue increasing to meet projected growth in freight demand.[4] Long-haul freight transport, which requires the largest power to haul the heaviest payload over the longest range across all on-road vehicles, is recognized as particularly difficult to decarbonize.[5] The goal of this study is to quantify the global climate change and local-level health impacts of long-haul freight electrification in the U.S.

Greenhouse gas (GHG) and local air pollutant emissions negatively impact society and the natural environment. GHG emissions lead to long-term climate change, which harms human health, agricultural yields, biodiversity, and productivity, while increasing energy consumption, conflict, mortality, and morbidity now and in the future.[6−8] Emissions of local air pollutants increase the ambient concentration of particulate matter (PM) and ground-level ozone, elevating the incidence of lung cancer, asthma, cardiovascular disease, and mental health diseases.[9−12] In 2010, the U.S. National Academies of Sciences, Engineering, and Medicine estimated that the transportation sector caused a toll of $110 billion in human health and environmental damages.[13] More recently, Davidson et al.[14] estimated that emissions from on-road vehicles contributed to 12,000−31,000 premature deaths in 2011 and will contribute 6700−18,000 premature deaths in 2025 in the United States, whereas Anenberg et al.[15] estimated that 22,000 premature deaths in the United States in 2015 were attributable to transportation tailpipe emissions. Regarding heavy-duty vehicles, a recent study finds that local air pollutant emissions from interregional diesel trucks lead to more than 3000 lives lost in the U.S. per year.[16] Research has shown that diesel hybrid-electric vehicles and natural gas vehicles have limited potential to mitigate health and climate damages from long-haul trucking,[17,18] suggesting that full electrification may be warranted.

Although light-duty electric vehicles are increasingly common due in part to the improved driving and charging

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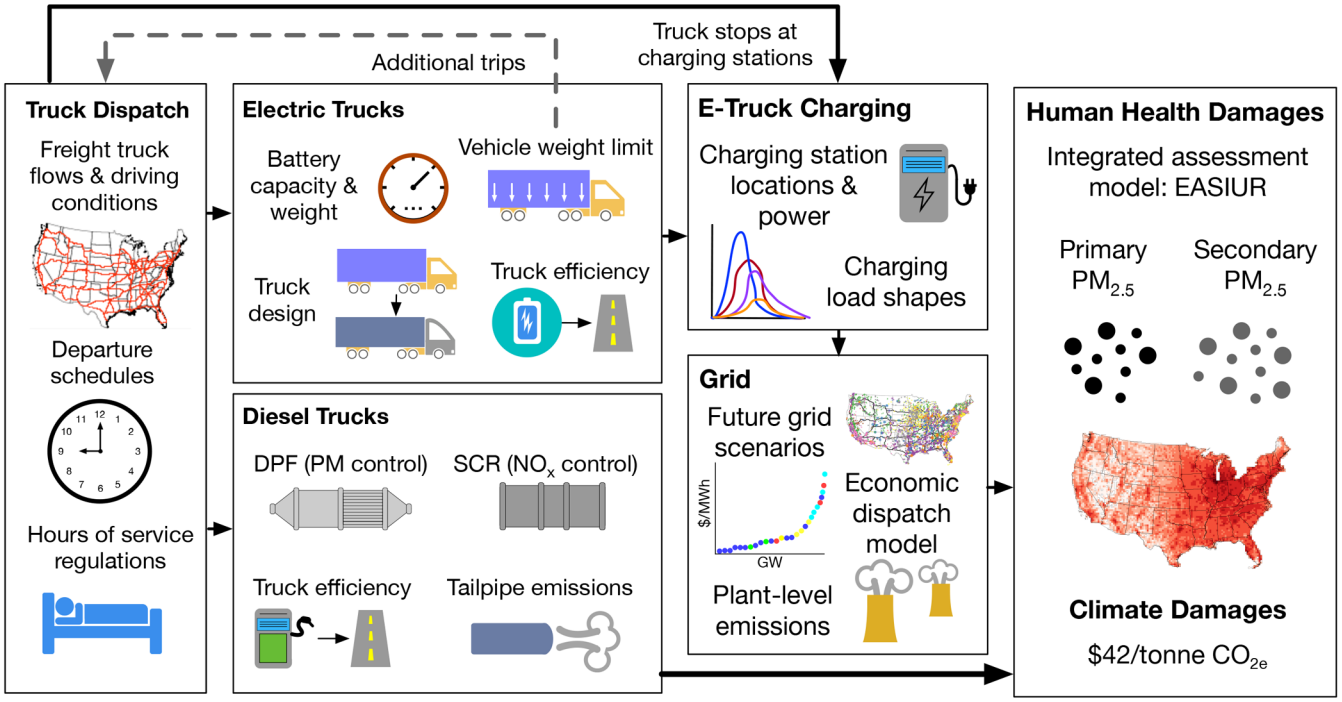

Figure 1. An integrated assessment approach to quantify energy, health, and climate impacts of electric and diesel long-haul trucks. The framework consists of freight demand model, vehicle energy model, truck flow and payload model, charging infrastructure model, truck dispatch and operation model, electricity grid model, diesel truck emissions inventory, and air quality integrated assessment models (that monetize health and climate damages of local air pollutant and greenhouse gas emissions).

experience,[19−21] fully electric vehicles were historically considered incapable of meeting the high-power and high-energy needs of long-haul trucks because of battery capacity constraints, prohibitive capital costs, and vehicle weight limits.[22,23] In the past three years, several truck manufacturers have unveiled fully electric heavy-duty trucks, enabled by rapid reductions in lithium-ion battery prices (from $1100/kWh in 2011 to $300/kWh in 2016 to as low as $100/kWh in 2020).[23−26] In this context of battery technology improvements and the urgent need to mitigate climate change, the State of California has mandated sales of zero-emission trucks as part of its Advanced Clean Trucks (ACT) regulation approved in 2020.[27] The goal of the ACT regulation is to accelerate the adoption of zero-emissions trucks (e.g., fully electric trucks and fuel cell electric trucks). Given California's market size and influence, other states across the U.S. will likely follow suit.

Although policymakers are establishing aggressive targets, only a handful of heavy-duty electric trucks have operated on-road, and most of these electric trucks are for testing or demonstration purposes on a limited scale.[28] In addition to an absence of real-world operation experience, prospective modeling and analysis of truck electrification are at best nascent and sporadic. Researchers at Carnegie Mellon University studied the feasible range of technical parameters (such as aerodynamic design, battery specific energy, battery capacity) for electric trucks to achieve technical performance comparable to diesel trucks.[29,30] These studies show a trade-off between vehicle payload and vehicle range of electric trucks for a given combination of design parameters and battery technologies. The results indicated that further improvements in battery technologies (i.e., higher battery specific energy) would be essential to achieve a meaningful payload (10 short tons) at a reasonable range (600 miles). Furthermore, Sripad et al. identified technical and economic targets (electricity price, battery pack price, battery lifetime, and vehicle drag coefficient) that would result in a five-year payback period for heavy-duty electric trucks compared to new diesel trucks.[31] Phadke et al. showed that charging electric trucks when time-of-use rates are low may substantially improve their economic competitiveness.[32]

Although these studies contributed to the body of knowledge on heavy-duty electric trucks' technical design and techno-economic assessment, none of these studies addressed the question of whether long-haul truck electrification would result in real-world health and climate improvements. This societal question is critical as the expected health and climate benefits from truck electrification are the primary motivation for public policy intervention.[22,27] For light-duty vehicles, which are comparatively well studied, recent work finds that vehicle electrification powered by current electricity grids may not lead to health benefits in some U.S. regions, although the growing share of renewable energy on the electric grid increases the likelihood of achieving widespread climate and health benefits.[33−35] Studies investigating heavy-duty trucks' environmental impacts are lacking, and existing studies solely focused on conventional diesel trucks.[16,36]

This study provides a comprehensive and systematic modeling framework to account for the climate and health impacts of a potential large-scale transition to truck electrification. To accomplish this goal, the modeling framework must first simulate a large-scale fleet of electric trucks informed by actual operation data, rather than just modeling one representative truck with a simplified operation pattern (which is the predominant approach used by prior studies[6,27,31]). Second, the framework must account for future

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grid scenarios and the nontrivial effect of long-haul truck charging on system-wide load and power plant dispatch. Commonly employed simple statistical representations of the electricity grid, which are only suitable for modeling marginal changes, cannot capture these grid impacts.[37,38] Electricity grid models that optimize electricity generation with detailed representations of electricity generation facilities and major transmission lines are needed. Finally, reduced-form air quality models that connect emissions with marginal health damages can be leveraged to estimate monetized health damages from vehicles and power plants, based on meteorology, atmospheric chemistry, epidemiology, and population density.[39,40]

■ METHODS AND DATA

To quantify the potential health and climate impacts from long-haul truck electrification, we developed an integrated assessment approach with high spatial-temporal (km and hourly) resolution to characterize the causal chain from truck operation to charging loads, electricity grid response, changes in emissions and atmospheric concentrations, and the resulting health and climate impacts across the United States (Figure 1; refer to Supporting Information (SI) for details). We linked a freight demand model with a vehicle energy model, truck flow and payload model, charging infrastructure model, truck dispatch and operation model, electricity grid dispatch model, diesel truck emissions inventory, and, finally, air quality integrated assessment model (Figure 1). To our knowledge, this is the first attempt to develop a comprehensive and systematic modeling framework for large-scale truck electrification with an explicit simulation of coupled engineering systems and the environment simultaneously.

We assumed a complete conversion to long-haul (battery) electric trucks for simplicity and transparency, as market adoption of emerging technologies is highly uncertain, depending on economic, regulatory, and technical factors. This study is confined to provide a first-cut quantitative understanding of the potential health and climate impacts from (large-scale) long-haul truck electrification due to the complexity and scale of the integrated assessment framework. We did not model other emerging zero-emission truck technologies (such as hydrogen fuel cell electric vehicles, low-carbon biofuels, renewable natural gas, and renewable diesel) or the market acceptance or competition of these zero-emissions technologies.

To address uncertainty in future technology development, we generated and compared 576 counterfactual scenarios that span across diesel truck design (six technology vintages), electric truck design (three scenarios of battery specific energy, two scenarios of battery capacities), truck dispatch (two scenarios), charging power (four scenarios), and electricity grid (two scenarios; SI Table S1). We used the latest available data on long-haul truck flows[41] and current hourly electricity demand.[42] We did not model the endogenous changes in freight flow or electricity load from all other sectors in response to long-haul truck electrification. However, the model presented here is flexible to incorporate future freight flow or electricity demand projections for scenario analysis.

Electric Truck Design. Electric truck design parameters include battery pack specific energy (160−320 Wh/kg), vehicle aerodynamics (current and projected future designs), battery capacity (1−2 MWh), and charging power (0.5−4 MW). To generate a tractable number of comparisons, we considered three technology scenarios for the battery-pack-level specific energy and vehicle aerodynamic designs: base-case (240 Wh/kg and incremental truck design improvements), pessimistic (160 Wh/kg and current truck design), and optimistic (320 Wh/kg and advanced truck design). Given that Li-ion battery specific energy has nearly tripled since 2010, a doubling in specific energy is ambitious, but potentially achievable. These assumptions are discussed at length in the SI, section S3 and Table S7.

Electric Truck Operation and Charging Load. We combined high-fidelity truck operation data[41,43] and a simplified physics-based vehicle energy model (as introduced in Sripad et al.[29]) to capture trucks' varying energy consumption under different driving conditions (such as truck speed, payload, and road grade; at ∼1 km). We simulated the dispatch and operation of electric trucks in a temporal resolution of 1 min based on simple decision rules given the physical and regulatory constraints, as described in detail in the SI. We assumed that charging stations are installed at highway intersections and within highway corridors to ensure coverage of the studied highway network.[43]

Electricity Grid Model. To accurately characterize truck electrification's full impact on electricity grid operation, we used an economic dispatch model (the GOOD model).[42] The model optimizes the operation of electric generation units (>8000 units across the United States) in an hourly resolution over a year, subject to engineering constraints for all existing and future power plants and major transmission lines. The model divides the contiguous U.S. into 64 regions defined by U.S. EPA's Integrated Planning Model. The capacity mix of electric power generators is exogenously determined to the GOOD model. We investigated two representative future electricity grid scenarios: a business-as-usual grid (the 2030 Reference Case projected by U.S. Energy Information Administration (EIA))[44] and an aggressive goal of a high-renewable grid in which renewable resources would generate >80% of electricity.[45] In both scenarios, fossil fuel-fired generating capacity decreases across the U.S. relative to current capacity. To account for this, we apply a uniform fractional decrease in capacity across each type of power plant on a region-specific basis rather than attempting to simulate specific plant retirements. For example, if coal generation capacity is expected to decrease by 50% in a given region (one of 64 total regions), all coal power plants in that region will be assigned half of their current generating capacity in the GOOD model. Both future grid scenarios also require expansion of solar and wind generation, but because those facilities do not directly emit pollutants, we do not assign specific locations to the new generation within each region. Baseline electricity demand is estimated using 2018 electricity demand for each region, and truck charging loads are assigned to each of the 64 regions based on simulated charging station locations and loads. Mathematical representation and key inputs and results for the GOOD model are available in the SI.

Emissions from Diesel Trucks. To provide a baseline technology for comparison, we included four types of currently operating diesel trucks and two types of future diesel trucks. Existing diesel trucks are characterized into four technology vintage groups primarily based on emissions control technologies, following a recent California field measurement study.[36] In the past four decades, two pollution control technologies, Diesel Particulate Filter (DPF) and Selective Catalytic Reduction (SCR), were developed and regulated to be implemented over time to reduce tailpipe emissions of

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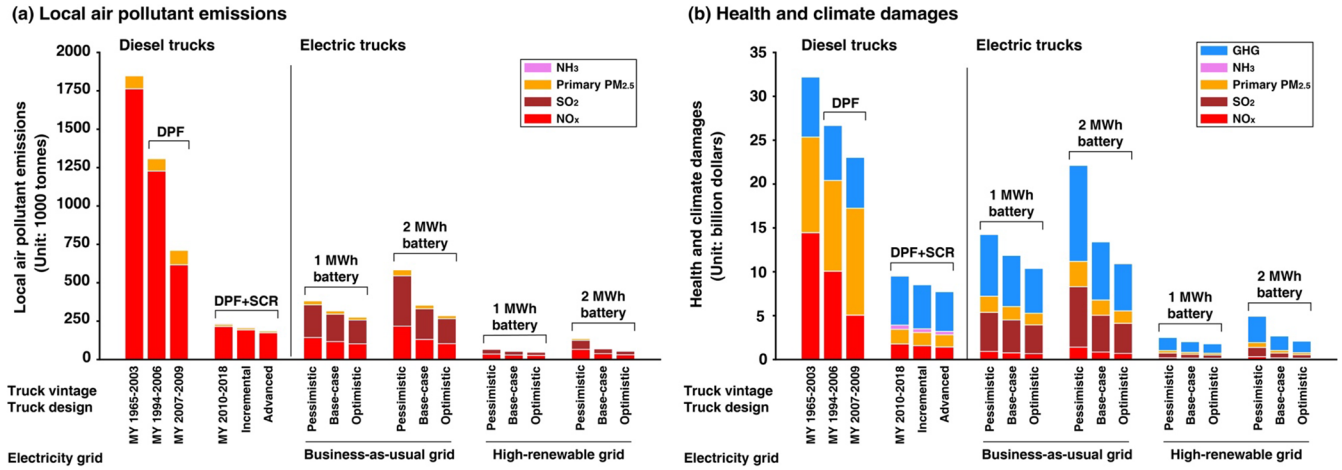

Figure 2. Comparison of local air pollutant emissions and health and climate damages between diesel trucks and electric trucks (1 MW charging power, late-charging scenario). Numeric values and results for greenhouse gas emissions are available in SI Table S14. (MY, Model Year; DPF, Diesel Particulate Filter; SCR, Selective Catalytic Reduction.).

particulate matter (DPF) and those of oxides of nitrogen (SCR).[36] The four technology vintage groups for currently operating diesel trucks include (1) Model Year (MY) 1965−2003 without DPF or SCR; (2) MY 1994−2006 retrofitted with DPF but no SCR; (3) MY 2007−2009 with DPF but no SCR; (4) MY 2010−2018 with DPF and SCR. Future diesel trucks are assumed to have the same pollution control technologies (DPF and SCR) as MY 2010−2018 diesel trucks.

We created representative profiles (tailpipe emissions factors and normalized fuel consumption; SI Table S8) for these six types of diesel trucks using a combination of measurement data, literature studies, and the GREET model.[17,36,46] The tailpipe emission factors by vintage and control technology are based on on-road measurements, and the individual vehicle-level reported data confirm the presence of superemitters as part of the set of vehicles that were measured to generate the fleet-average values.[36] We first selected and categorized studies by the truck technology vintage group. We then scaled the reported emissions factors from the selected studies to match the representative normalized fuel consumption for the corresponding truck technology vintage group assuming a linear relationship between tailpipe emissions and fuel consumption. Furthermore, we estimated in-use tailpipe emissions of diesel trucks driving on the highway network by scaling the representative tailpipe emissions profiles with the ratio of the in-use specific fuel consumption (calculated from the vehicle energy model) and the fleet-average specific fuel consumption. We note that this first-order approximation might induce error into this estimation but do not believe it affects the overall conclusions of our research.

Monetized Climate and Health Impacts. For the assessment of monetized climate and health impacts, we considered local air pollutants (NO_x, SO_2, fine particulate matter ($PM_{2.5}$), NH_3) and GHG (CO_2, CH_4, and N_2O) emissions. We adopted a damage-function approach to estimate the monetized health and climate damages.[13] Namely, the damages are calculated as a product of the mass of emissions and the corresponding marginal damages for species (s) at a location (l) and a height (h). Marginal damages for local air pollutants (NO_x, SO_2, $PM_{2.5}$, and NH_3) are sensitive to location and height of emissions, but marginal damages of GHG emissions (i.e., the social cost of carbon[47]) are considered constant irrespective of location and height due to the global nature of this pollutant. For the results discussed below, we included tailpipe emissions from diesel trucks and stack emissions from power plants (attributed to the additional electricity demand for truck electrification). Additionally, we calculated separate damage estimates for upstream emissions associated with primary energy extraction and battery manufacturing. We chose to discuss these damages separately because they heavily relied on the literature estimates.

We monetized health impacts from the increased local air pollution emissions using a state-of-the-art reduced-form integrated assessment model, the EASIUR model.[39] The EASIUR model integrates a baseline emissions inventory, atmospheric dispersion and chemistry, population exposure, a public health concentration-response function for $PM_{2.5}$, and the value of a statistical life (VSL) to generate annual damage estimates for NO_x, SO_2, primary $PM_{2.5}$, and NH_3 emissions (all based on their contribution to primary and secondary $PM_{2.5}$ concentrations) in a grid of 112 × 148 cells (each with a spatial resolution of 36 × 36 km) at three heights, 0, 150, and 250 m.[39] Ground-level ozone formation is not considered. The health damages captured include epidemiologically determined contributions to cardiovascular mortality and lung-cancer mortality risk but do not incorporate morbidity (e.g., chronic asthma). The EASIUR model also calculates the source-receptor matrix for each species of local air pollutant emissions, which has a dimension of 112 × 148 × 112 × 148 or more than 274 million individual values. The source-receptor matrix is essential to quantifying the spatialized health impacts across the contiguous United States resulting from truck electrification (refer to Figure 3). For the monetized health damages, we assumed a VSL of \$8.6M.[39] The monetized health impacts of local air pollutants are highly uncertain and subject to ongoing scientific investigation.[34,39,40] To calculate climate damages, we used a Social Cost of Carbon (SCC) of \$42/tonne CO_2.[47] We converted short-lived climate pollutants to carbon dioxide-equivalent emissions using 100-year global warming potential (36 for fossil fuel CH_4 and 298 for fossil fuel N_2O).[48] The SCC estimate is profoundly uncertain, mainly due to modeling choices, such as the discount rate or underlying damage function.[47] Finally, we reported monetized health and climate

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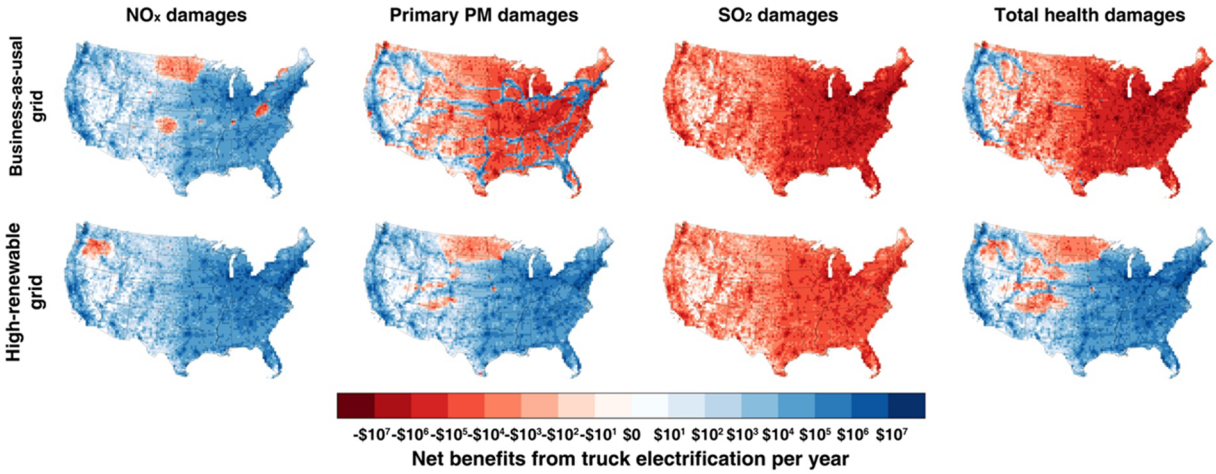

Figure 3. Spatial distribution of health benefits from a transition of (advanced design) diesel trucks to electric trucks (1 MWh battery, 1 MW charging power, late-charging scenario). We consider two scenarios for electric trucks: (1) a conservative scenario (top panel), base-case electric trucks charged by the business-as-usual grid, and (2) a policy scenario (bottom panel), optimistic electric trucks charged by the high-renewable grid. Total health damages include those caused by primary $PM_{2.5}$ emissions and secondary $PM_{2.5}$ formation resulting from NO_x, SO_2, and NH_3 emissions.

Table 1. Comparison of Health and Climate Damages between Fleets of Diesel Trucks and Electric Trucks (1 MWh Battery, 1 MW Charging Power)[a]

Electric truck			Diesel truck					
Electricity grid	Truck design	Truck operation & charging	MY 1965-2003 No DPF	MY 1994-2006 Retrofitted w/ DPF	MY 2007-2009 DPF	MY 2010-2018	Incremental DPF + SCR	Advanced
Business-as-usual grid	Pessimistic	Early charging	57%	48%	40%	-45%	-61%	-78%
		Late charging	56%	47%	38%	-50%	-67%	-84%
	Base-case	Early charging	65%	57%	51%	-20%	-33%	-47%
		Late charging	63%	55%	48%	-25%	-39%	-54%
	Optimistic	Early charging	69%	63%	57%	-4%	-16%	-28%
		Late charging	68%	61%	55%	-9%	-22%	-34%
High-renewable grid	Pessimistic	Early charging	96%	95%	94%	85%	84%	82%
		Late charging	92%	91%	89%	74%	71%	67%
	Base-case	Early charging	97%	96%	95%	88%	87%	86%
		Late charging	94%	92%	91%	79%	76%	74%
	Optimistic	Early charging	97%	97%	96%	90%	89%	88%
		Late charging	94%	93%	92%	81%	79%	77%

[a]A relative difference of +50% represents that electric trucks reduce 50% of damages compared to diesel trucks, whereas −50% indicates that electric trucks increase 50% of damages. (DPF: Diesel Particulate Filter, SCR: Selective Catalytic Reduction.).

impacts in 2010 U.S. dollars based on the consumer price index.[49]

Upstream Energy Activities. The recent literature estimated normalized damages from upstream energy activities (i.e., coal mining and transport, oil and gas extraction, and oil refinery) for the U.S. using county-level energy production and county-level emissions data.[34] We quantified primary energy consumption for the operation of diesel trucks and electric trucks. We then multiplied primary energy consumption with normalized damages to calculate upstream damages for national fleets of diesel trucks and electric trucks.

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Battery Manufacturing. We relied on the literature for normalized damages from battery manufacturing.[33,50] We then considered the energy capacity of installed batteries in electric trucks, the replacement of batteries during a truck's lifetime, and the lifetime driving distance of electric trucks to calculate battery manufacturing damages for the national fleet of electric trucks.[30] We implicitly assumed that emissions and damages associated with the manufacturing of diesel tractors and electric tractors (not including batteries) are comparable.

■ RESULTS AND DISCUSSION

Health and Climate Impacts of Diesel Trucks. Modern tailpipe pollution control technologies (DPF and SCR) have decreased emissions of local air pollutants from diesel trucks and achieved sizable health benefits compared to older vehicles without DPF and SCR (Figure 2).[36] Barring any unexpected advances in tailpipe emissions control or engines, we find that further health benefits from projected future improvements in pollution control and fuel efficiency technologies in diesel trucks are incremental compared to Model Year (MY) 2010–2018 trucks (Figure 2). This is because pollution control technologies (DPF and SCR) cannot capture all tailpipe emissions from diesel trucks due to physical and chemical constraints—even when they work perfectly.[36] Because our results are based on measured on-road emission factors, they also account for the fact that, in real-world driving conditions, pollution control technologies do not always work as designed, and a small number of superemitters can have an outsized impact on fleet-wide emissions.[36]

Health and Climate Impacts of Electric Trucks. The environmental impacts of electric trucks are highly dependent on the electricity grid generation mix (Figures 2 and 3 and Table 1). While we provide a large number of comparisons between the fleets of electric trucks and their conventional counterparts, we highlight two critical comparisons. The first comparison is between 1 MWh battery base-case electric trucks charged by the business-as-usual electricity grid and a fleet of future advanced-design diesel trucks. The rationale is that new electric trucks with projected technology improvements must be compared to the counterfactual new purchase (modern diesel trucks) as opposed to the current diesel truck fleet. For this comparison, we show that electric trucks could lead to significantly higher (47–54%) health and climate damages relative to future diesel trucks. For both diesel trucks and electric trucks, total social damages are split approximately evenly between human health damages from $PM_{2.5}$ (sum of primary and secondary $PM_{2.5}$) and climate damages.

The second comparison considers more aggressive battery technology development and an electricity grid in which renewable energy resources supply 80% of U.S. net electricity generation. In this scenario, we assumed that the battery specific energy doubles relative to the current state-of-the-art, reaching 320 Wh/kg. The diesel truck fleet is still based on the advanced diesel truck design, consistent with the previously described scenario, to facilitate cross-comparison. In this case, electric trucks would lead to a 77–88% reduction in health and climate damages relative to diesel trucks. Furthermore, for electric trucks, climate damages comprise a larger share of total social damages relative to health damages. The greater reduction in health damages for electric trucks in this scenario is due to the following two factors: (1) eliminated tailpipe emissions from electric trucks and (2) the marginal electricity generation mix that would charge electric trucks (while still relying partially on fossil power plants in some regions) is considerably cleaner than those in the business-as-usual electricity grid scenario.

A shift from diesel trucks to electric trucks changes both the spatial distribution and the composition of air pollutants emitted. Diesel trucks' emissions originate from a large number (hundreds of thousands) of mobile sources at ground level. By comparison, electric trucks' emissions sources are limited to less than 9000 continuously monitored-and-regulated power plants. Furthermore, the types of emissions also differ: diesel trucks lead to a large quantity of NO_x and primary $PM_{2.5}$ emissions, whereas fossil-fuel power plants primarily emit NO_x and SO_2 emissions to generate electricity for electric trucks (SI Tables S14 and S15).

The change in emission inventories leads to substantial spatial heterogeneity in net health benefits/damages when we model a complete transition from future diesel trucks to electric trucks (Figure 3). If we only account for NO_x emissions, a transition to electric trucks results in net health benefits across most of the United States. However, a shift to electric trucks would increase SO_2-related health damages, even with the high-renewable electricity grid (which still has a fraction of coal-fired electricity on the margin). This is because the diesel fuel's sulfur content is already very low (less than 15 ppm). The effect of primary $PM_{2.5}$ emissions depends on the composition of the electricity grid. For the business-as-usual electricity grid, the regions with positive health benefits coincide with freight corridors. However, this benefit comes at the expense of populations living farther from highways, where emissions from power plants dominate. In this case, the highly localized damages from ground-level truck-emitted $PM_{2.5}$ emissions are traded for widely distributed damages from elevated emissions out of power plant smokestacks. However, this pattern does not persist if the electricity grid is deeply decarbonized. The high-renewable electricity grid enables electric trucks to deliver primary-PM-related health benefits for most of the United States. For the ammonia-related health impacts, electric trucks will always result in net health benefits compared to diesel trucks equipped with SCR (a NO_x emissions control technology), which leads to tailpipe ammonia (NH_3) emissions.

When we consider the sum of health damages across local air pollutants (NO_x, SO_2, $PM_{2.5}$, NH_3), a fleet of electric trucks charged by the business-as-usual electricity grid would lead to net health benefits for residents on the West Coast but increase health damages for those living in the other parts of the United States. Substantial penetration of renewable energy (or other forms of zero-emissions electricity) in the electricity grid is essential to ensuring electric trucks' health benefits across the US. Still, some populations would face increased damages regardless (compared to a counterfactual scenario of future diesel trucks) because they live far from major freight corridors and close to the remaining fossil fuel-powered electricity generation facilities—such as those in the Rocky Mountain region and Upper Midwest.

Regional Variations in Health and Climate Damages. Variations in grid mixes, population density, and local meteorology all impact the degree to which truck electrification will increase or decrease air pollution-related health burdens on nearby communities. While the impacts of climate change are felt globally, the GHG emissions themselves vary based on regionally varying grid mixes across the U.S. Thus, it is crucial to evaluate the environmental impacts of truck

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Table 2. Summary of Normalized Health and Climate Damages of Diesel Trucks and Electric Trucks by Electricity Grid Region in the United States ($/1000 km)[a]

	diesel truck						electric truck (1 MWh battery, 1 MW charging power)											
	advanced design						base-case						optimistic					
	N/A						business-as-usual grid						high-renewable grid					
electricity grid region[b]	NO_x	SO_2	$PM_{2.5}$	NH_3	GHG	total	NO_x	SO_2	$PM_{2.5}$	NH_3	GHG	total	NO_x	SO_2	$PM_{2.5}$	NH_3	GHG	total
FRCC	7	0.1	12	3	40	61	1	1	4	0	31	37	1	8	3	0	13	25
MRO	16	0.1	10	2	40	67	8	30	15	0	45	98	3	11	4	0	16	34
NPCC	30	0.2	27	8	40	105	18	9	20	0	21	68	2	0	2	0	3	7
RFC	25	0.2	22	7	40	93	14	91	24	0	60	189	1	4	2	0	4	11
SERC	10	0.1	11	3	40	64	5	27	13	0	48	92	0	2	1	0	3	6
SPP	7	0.1	7	1	40	54	11	42	21	0	98	171	1	4	3	0	15	22
TRE	5	0.1	9	2	40	56	2	13	9	0	45	69	0	1	2	0	19	23
WECC[c]	4	0.1	4	1	40	49	2	5	4	0	52	62	2	2	2	0	18	24
California	11	0.1	11	1	40	63	2	0	5	0	27	34	1	0	1	0	6	8
United States	12	0.1	12	3	40	68	7	33	13	0	51	104	1	3	2	0	9	16

[a]Acronyms: GHG = greenhouse gases. [b]These regional results are calculated based on national-fleet results. The definition of electricity grid region is in Figure S1. [c]Here, WECC region excludes California.

electrification by region to inform and prioritize infrastructure development and electrification efforts. In Table 2, we summarized normalized health and climate damages ($ per 1000 km) by the (aggregated) electricity grid region based on the results for the U.S.-scale fleet of electric trucks and diesel trucks (i.e., those shown in Figures 2 and 3). We also reported normalized health and climate damages in terms of $ per 1000 tonne-km in Table S19 (SI).

Normalized health and climate damages of electric trucks are sensitive to the electricity grid mix (i.e., electricity source that meets truck charging demand). With the business-as-usual electricity grid, electric trucks used in regions that are less dependent on coal-fired power plants (e.g., California, Florida, and New England) achieve lower normalized damages than diesel trucks. In coal-heavy regions (e.g., Kansas and Mid-Atlantic region), electric trucks more than double the normalized damages compared to diesel trucks. It is important to note that electric trucks charged with a high-renewable electricity grid would result in lower normalized damages than even the best future diesel truck technology in every U.S. region.

Impact of Battery Technology Improvements. Projected battery technology development is essential for truck electrification. A slower-than-expected technology improvement (i.e., the pessimistic case of battery specific energy) would result in additional vehicle distance traveled, increased energy consumption, and much higher health and climate damages for electric trucks, especially for 2 MWh electric trucks (Figure 2). Also, a loss of more than 50% cargo capacity (by weight) for 2 MWh electric trucks (compared to future diesel trucks) would likely be a significant technical and economic barrier for the adoption of such trucks (SI Table S10). However, if technology advancements occur more rapidly (i.e., the optimistic case of battery specific energy), 2 MWh electric trucks could haul the same cargo without incurring any additional penalty.

Impact of Charging Power and Truck Charging Scenario. The results indicate that charging power does have an impact on the shape of load profiles (SI Figure S3), but in the scenarios evaluated here, it does not meaningfully impact electric trucks' health and climate damages (SI Figure S12). Truck charging scenarios, however, can have a more substantial impact depending on the grid mix. We varied electric trucks' charging time (i.e., they shift truck charging load earlier or later across a day) for each grid scenario to understand effect on electric trucks' health and climate damages (Table 1). Assuming the business-as-usual electricity grid, the early charging scenario and the late-charging scenario lead to comparable total damages. However, for the high-renewable electricity grid, total damages resulting from the late-charging scenario are more than twice those from the early charging scenario (SI Figures S11 and S13). This is because, in the high-renewable electricity grid, renewable resources may not always meet the additional load from truck electrification due to the variable nature of such resources. Fossil-fuel power plants would be dispatched to meet the truck charging load at times without extra renewable energy, leading to much higher emissions and substantial health and climate damages.

Comparison with Existing Studies. We presented a detailed comparison of the estimated health damages from this study and the existing literature[16,18,51] in the SI. None of the prior work considered long-haul truck electrification, so the comparison is focused on long-haul diesel trucks. We find that the estimated energy, emissions, and health impacts for long-haul diesel trucks between this study and Liu et al.[16,51] are similar. After harmonizing the assumed truck activity, estimates from this study are within the 50% relative range of those reported in the existing literature (SI Tables S2 and S3). The normalized health damages for long-haul diesel trucks in this study are on the same order of magnitude as those in Tong.[18]

Emissions Accounting and Attribution of Electricity-Related Emissions. There is an ongoing debate in the literature regarding marginal electricity generation versus average electricity generation in the attribution of electricity-related emissions to electric vehicles.[34] The results shown above follow the marginal approach, which assumes that the electricity grid would meet the existing electricity demand first before the charging load from truck electrification. Because of resource, technical, and economic considerations, power plants on the margin are usually more emissions-intensive than the average electricity mix. Indeed, we find that the emissions intensity on the margin is about twice as large as the average mix for both future electricity grid scenarios (i.e., business-as-usual and high-renewable; SI Table S15; see also the dispatch

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curve for the electricity grid in Figures S7 and S8). As a result, electric trucks' health and climate damages estimated using the average approach are substantially lower than those using the marginal approach (SI).

Upstream Energy Activities. Diesel trucks lead to larger upstream damages than electric trucks. For future diesel trucks, upstream damages account for about 17% of those from vehicle operation (such as those shown in Figure 2). Upstream damages associated with energy production (e.g., natural gas for power plants) are relatively smaller for electric trucks, representing 9−12% of those from vehicle operation. Further details are provided in SI section S6.1.

Battery Manufacturing. Health and climate damages from battery manufacturing are sensitive to the normalized damages reported from the literature and batteries' lifetime. Estimating these damages becomes complex because material production and battery manufacturing occurs across multiple countries, and this article is focused on scenarios in which battery manufacturing happens within the U.S. According to recent literature, the total health and climate damages from battery manufacturing may range from $1.4 billion to $7.3 billion for a national fleet of 1 MWh electric trucks, depending on which estimate for normalized battery manufacturing damages is used (see SI section S6.2 for further details). Compared to the truck electrification scenarios with the business-as-usual grid as shown in Figure 2, these damages are an order of magnitude smaller. However, if battery manufacturing occurs in countries that continue to rely on fossil fuels for electricity generation and industrial heat, these upstream damages may be on par with those associated electric truck charging. Health damages associated with battery manufacturing in other countries will also depend on distributions of local populations and meteorology in areas where emissions occur, adding additional uncertainty. Further study on this topic is warranted.

Study Limitations. A key limitation of this study is that the truck flows and energy demand are based on current patterns of long-haul freight trucking. In reality, freight patterns will change over time due to shifts in the flow of goods domestically and internationally, relative costs of different freight modes, as well as the emergence of new technologies changing the supply chain. We do not explicitly model these changes in this study. Innovative use of the emerging "big data," such as those collected by electronic logging devices,[52] cellphones,[53] and traffic sensors,[54] has great potential to improve the modeling of freight flows and truck traffic. Further, we do not quantify the effect of traffic congestion on emissions from diesel trucks.[55] Finally, we do not quantify the effect of weather on the performance of electric trucks, which is known to impact battery performance and overall vehicle efficiency.[56]

An additional study limitation is associated with our use of a reduced-form air quality model (EASIUR). The use of EASIUR enables an investigation of a wide range of scenarios (over truck design, battery technology, truck dispatch, truck charging, and the electricity grid). However, any reduced-form model will be limited in its ability to accurately capture atmospheric chemistry and physics (EASIUR, for example, does not provide an ability to model the impacts of volatile organic compounds, which are precursors to secondary $PM_{2.5}$).[34,39,40] As a result, our results may underestimate the health benefits of truck electrification in some areas. Our analysis also does not include the carcinogenic risk specific to diesel PM,[57] nor does it include nonair quality, nonclimate impacts such as noise from diesel trucks,[58] which truck electrification can partially mitigate.

Truck Charging Schedules and Safety Considerations. One might question our decision not to develop and optimize charging schedules based on when marginal damages from electricity-related emissions are lowest. Our choice not to optimize charging schedules is based on an assumption that flexibility in charging schedules is limited because drivers are constrained by operating hours at ports and warehouses (and other originals and destinations), as well as mandated rest times. Driving safety is a policy priority for federal regulation on long-haul trucking.[59] The U.S. Federal Motor Carrier Safety Administration has recently mandated using electronic logging devices (ELDs) to track, manage, and maintain duty status records for truck drivers.[52] However, ELDs may not ensure that truck drivers take rests when required and the impact of truck electrification on compliance with mandated rest times is unclear. Implementing time-of-use charging to incentivize drivers to charge vehicles at particular times of day could have unintended impacts on safety if drivers respond to pricing signals by delaying rest and vehicle charging times to align with lower-cost rates. At a minimum, this study highlights the importance of factoring realistic schedules and rest times when modeling truck electrification. Further study is warranted to ensure that electricity rate structures meant to maximize environmental benefits do not negatively impact safety, assuming electrified trucks are not primarily relying on autonomous driving technologies. Although charging infrastructure placement was not a focus of this study, availability of charging stations must be sufficient such that drivers do not feel a need to delay rest times to ensure access to a charging station.

Co-Development of Charging Infrastructure and the Electricity Grid. A final consideration that warrants future work is the path from today's infrastructure to full (or partial) electrification of long-haul freight trucking. This paper focuses on snapshots of potential futures, based on full electrification of long-haul freight trucking using a business-as-usual grid and an ambitious 80% renewable grid as a theoretical best-case scenario. It is also based on unlimited charging capacity at individual stations (with charging power for individual trucks varying between 0.5 and 4 MW). These high-power charging stations require new generation capacity and transmission and distribution infrastructure. Further exploration of private and social cost trade-offs for different infrastructure build-out scenarios can leverage our work to identify and prioritize corridors that will provide the greatest benefit from early infrastructure investments.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.est.1c01273.

> Additional literature review and methodological assumptions on long-haul truck operations, diesel and electric truck technologies, energy use, emission factors, grid scenarios and dispatch modeling, and upstream health and climate damages; full set of results across all truck technology, charging power, dispatch, and grid scenarios (PDF)

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Author Contributions

The authors confirm contribution to the paper as follows. Study conception: C.S. and M.A. Study Design: F.T., A.J., D.W., C.S., and M.A. Data collection: F.T., A.J., D.W. Analysis: F.T., A.J., D.W. Interpretation of results: F.T., A.J., D.W., C.S., and M.A. Author; draft manuscript preparation: F.T., A.J., D.W., C.S., and M.A. All authors reviewed the results and approved the final version of the manuscript.

Notes

The authors declare no competing financial interest.

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