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LETTER

Lightweighting cost impacts on market adoption and GHG emissions in U.S. light-duty vehicle fleet

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Abstract

Vehicle lightweighting is a promising strategy that can reduce energy consumption and GHG emissions without compromising vehicle's performance or size. The cost of lightweighting plays a critical role in determining the adoption of lightweighting technologies by consumers and manufacturers among advanced vehicle technologies. This analysis estimates the cost of lightweighting needed to achieve significant light-duty vehicle adoption to provide reductions in use-phase GHG emissions. Three different costs of lightweighting scenarios in the U.S. market including a baseline scenario, advanced technology scenario, and widespread scenario are evaluated employing Automotive Deployment Options Projection Tool (ADOPT) in conjunction with other technology improvement assumptions (e.g., advancements in fuel and battery technologies, and material price reductions) from DOE. ADOPT leverages a database of over 700 existing vehicle models and options, enabling it to provide a high degree of realism and capture the unique characteristics of popular vehicles and the endogenously evolvement of the vehicle options. For baseline scenario, the use-phase GHG emissions are reduced by more than 50% and lightweighting fraction reaches 15% by 2046 compared to 2015 levels. The widespread scenario further reduces the GHG emissions by about 4% from the additional 10% glider mass reduction compared to the baseline scenario. The benefit came largely from lightweighting being implemented in the large market segment of lower-price vehicles, due to the relatively low lightweighting cost ($5/kg).

1. Introduction

Transportation plays a crucial role in energy consumption and greenhouse gas (GHG) emissions in the United States, which contribute to 27% of energy usage and 36% of the GHG emissions in 2022 [1, 2]. These figures amount to more than 27 quadrillion Btu and 1,809 million metric tonnes of CO_2 equivalent emissions [1, 2]. Among the various transportation sectors, light-duty vehicles stand out as the primary contributor, representing 54.2% of total energy consumption and 58% of total GHG emissions [1, 2]. Consequently, numerous innovative technologies have emerged and gained traction to mitigate energy consumption and GHG emissions in the transportation sector such as electric vehicles and lightweighting materials.

Lightweighting materials have the potential to significantly enhance vehicle efficiency and reduce GHG emissions. Research findings reveal that a 10% reduction in vehicle mass can lead to a 6%-8% improvement in fuel economy and corresponding GHG emissions [3–5], supporting environmental sustainability goals. The current market trend within the US exhibits a growing preference among customers for larger vehicles, specifically SUVs and pickup trucks within the light-duty vehicle segment [3]. This preference is primarily driven by the allure of larger space, increased comfort, and safety features that these larger vehicles provide [4]. Amidst this backdrop, the advantages accrued from lightweighting and other advanced technologies have been

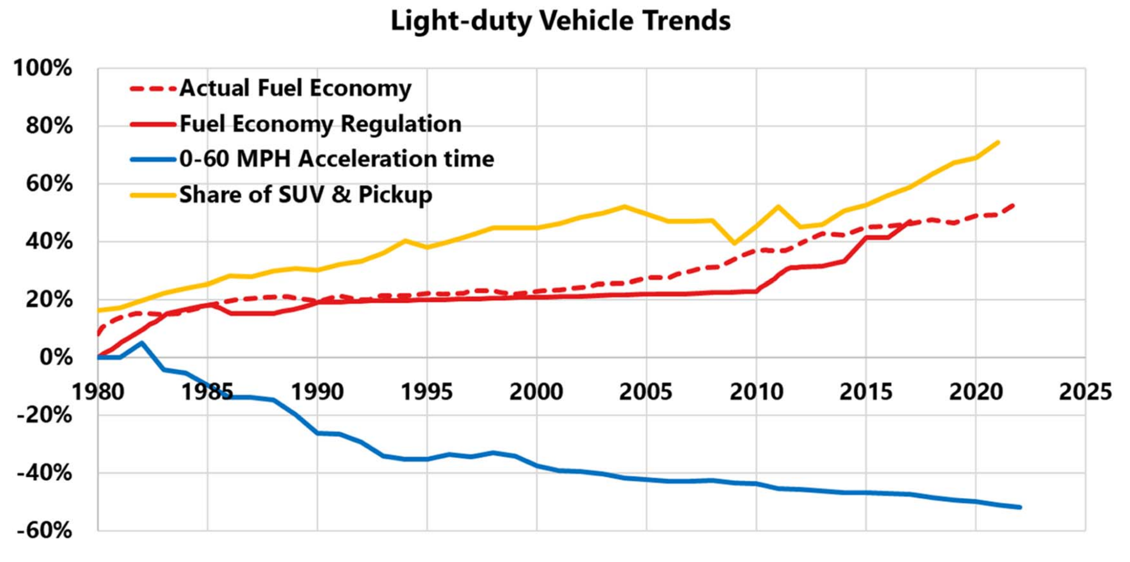


Figure 1. Historical light-duty vehicle trends.

significantly channeled towards augmenting the size and performance of vehicles, rather than solely improving fuel economy [6, 7], as illustrated in figure 1. Thus, exploring the impact of lightweight materials' adoption in the market on the automotive industry's journey towards sustainability becomes pivotal.

Automotive manufacturers are currently adopting lightweight materials incrementally, aiming to cut down weight and manufacturing and operating cost through material savings while enhancing vehicle performance metrics like acceleration, braking, energy efficiency, and emissions [5]. Nevertheless, the incremental upfront cost implications of adopting lightweight materials may influence industry acceptance and consumer preference, owing to the associated premium expenses of the lightweight materials. Therefore, a comprehensive assessment of lightweighting upfront material cost implications on GHG emissions and energy benefits within the U.S. light-duty vehicle fleet is essential to ensure a holistic understanding of all intertwined factors and issues.

Many analyses have focused on the energy and GHG emission benefits of lightweighting [6–10]. Some have focused on the fuel economy benefit considering a downsized engine and the trade-off between vehicle performance and fuel economy, and how that impacts GHG emissions [6, 8–13]. Some studies investigated the energy and GHG benefits from lightweighting at the specific powertrain level [9, 14, 15]. Several studies have examined the trade-off between lightweight material production and vehicle operation phases [11, 16, 17]. These investigations revealed that greenhouse gas (GHG) emissions associated with lightweight material production can vary significantly depending on the local energy grid mix, due to the energy-intensive nature of some production processes such as aluminum smelting. Nevertheless, the adoption of lightweight materials is highly likely to reduce overall life cycle GHG emissions, regardless of the vehicle's powertrain types. Several studies have gone further to explore the potential lightweighting energy consumption and GHG emissions impacts at the fleet level considering the new vehicle design and/or powertrain [18–23]. However, little information is available on the fleet-scale effects considering the interaction between lightweighting and other technology developments. Furthermore, the adoption of novel technologies depends on numerous factors such as cost, consumer preferences, regulatory guidelines, and the feasibility of assimilating the technology into the manufacturing framework. Therefore, it's imperative to incorporate the advanced vehicle technologies and the dynamics of the market especially in the long-term predictions in a validated customer choice model to estimate the market adoption of these technologies and the corresponding influence on energy consumption and greenhouse gas (GHG) emissions.

This analysis aims to bridge the identified gaps by capturing the earlier discussed elements - consumer preferences concerning performance and size versus electric range and fuel cost, the impact of regulations, and the role of purchase incentives. Through this analysis, a more accurate understanding of the market conditions essential for realizing the fuel economy and GHG emission benefits of lightweighting will be achieved. In this analysis, we proposed to employ The Automotive Deployment Options Projection Tool (ADOPT), a significant innovation in vehicle modeling, estimates customer uptake of lightweighting at different cost levels [11]. It leverages a database of over 700 existing vehicle makes, models, and options, enabling it to provide a high degree of realism and capture the unique characteristics of the best-selling advanced vehicles in the market, while also being able to endogenously evolve the vehicle options based on market conditions, regulations, and incentives, including the level of lightweighting. This analysis aims to estimate the cost of lightweighting needed to achieve

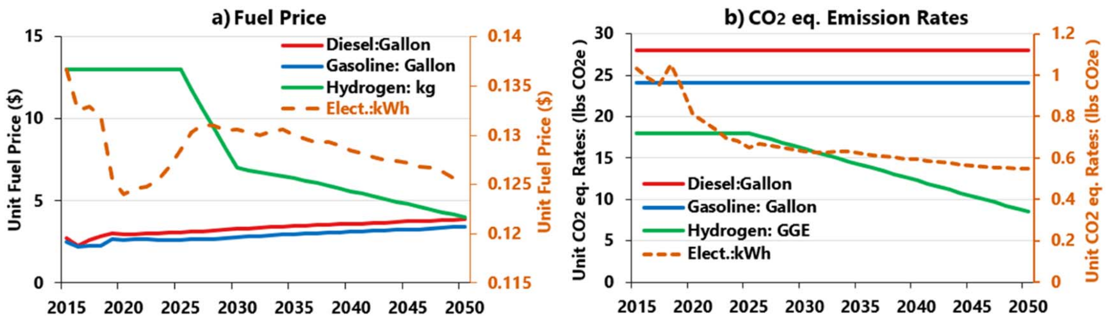


Figure 2. AEO 2020 reference case fuel and hydrogen fuel price and carbon intensity assumptions (GGE: Gasoline Gallon Equivalents).

significant light-duty vehicle adoption to provide reductions in energy consumption and GHG emissions. Three different costs of lightweighting scenarios in the U.S. market including a baseline scenario, advanced technology scenario, and widespread scenario are evaluated.

2. Assumptions and inputs

A variety of assumptions and data are required for this analysis; it assumes that light-duty travel continues primarily by private vehicles, and its scope does not delve into potential impacts from large-scale changes to this paradigm, such as travel shifting to a ride-hailing model and/or automated vehicles that drive themselves. It also assumes technological improvements favorable to electrification more than biofuels or hydrogen pathways.

Technology improvement assumptions are applied to vehicles over time during the ADOPT simulations. All the scenarios use a set of technology improvement assumptions from DOE's Vehicle Technologies Office and Hydrogen and Fuel Cell Technologies Office that result in a significant change to vehicle electrification.

2.1. Fuel price

The fuel price assumptions used in this analysis are primarily sourced from AEO 2020 as illustrated in figure 2. However, it is important to note that for hydrogen, the assumptions and goals are based on the baseline guidelines provided by the Hydrogen and Fuel Cell Technologies Office. A trend can be observed where fuel prices for hydrogen and electricity are generally declining from 2015 to 2050. Contrastingly, gasoline and diesel prices tend to remain relatively stable, with a slight increase observed from 2015 to 2050.

2.2. GHG emissions

All fuel emissions assumptions (except for hydrogen) are sourced from AEO 2020, which focuses on a 'well-to-wheel' or lifecycle approach for calculating emissions from transportation fuels. This approach includes emissions from fuel production, processing, distribution, and end-use combustion. As illustrated in figure 2(b), there is a decrease in the unit CO_2 equivalent emission rate for electricity over time, indicating that the electricity generation mix is becoming greener in the future. For Hydrogen, it is assumed to move from steam-methane-reformed hydrogen in 2015 to hydrogen produced via electrolysis with renewable electricity in 2050 per the Greenhouse Gases, Regulated Emissions, and Energy Use in Technologies (GREET) model [24]. However, it should be clarified that this representation is not intended for a direct side-by-side comparison, as it does not account for the variations in vehicle efficiency associated with each fuel type. The unit GHG emissions of diesel and gasoline remain stable, while the unit GHG emissions of hydrogen and electricity are anticipated to decrease by more than 40% from 2015 to 2050.

2.3. Battery prices

The battery price assumptions reflect those provided by DOE's Vehicle Technologies Office, as shown in figure 3(a). The chart shows the price for a 60-kWh battery as an example, which is expected to decrease over time, potentially reaching a unit price of less than \$100/kWh around 2025. The battery price per unit energy increases for smaller, higher-power batteries. The price assumption reflects prices aimed at decarbonizing the light-duty transportation sector through electrification. It is applied each year across all vehicle options that have traction batteries.

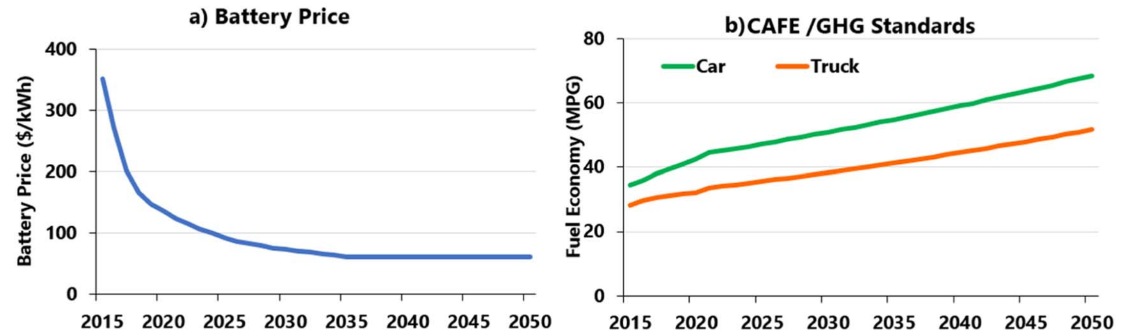


Figure 3. Battery price assumptions at 60 kWh and CAFE/GHG standard assumptions.

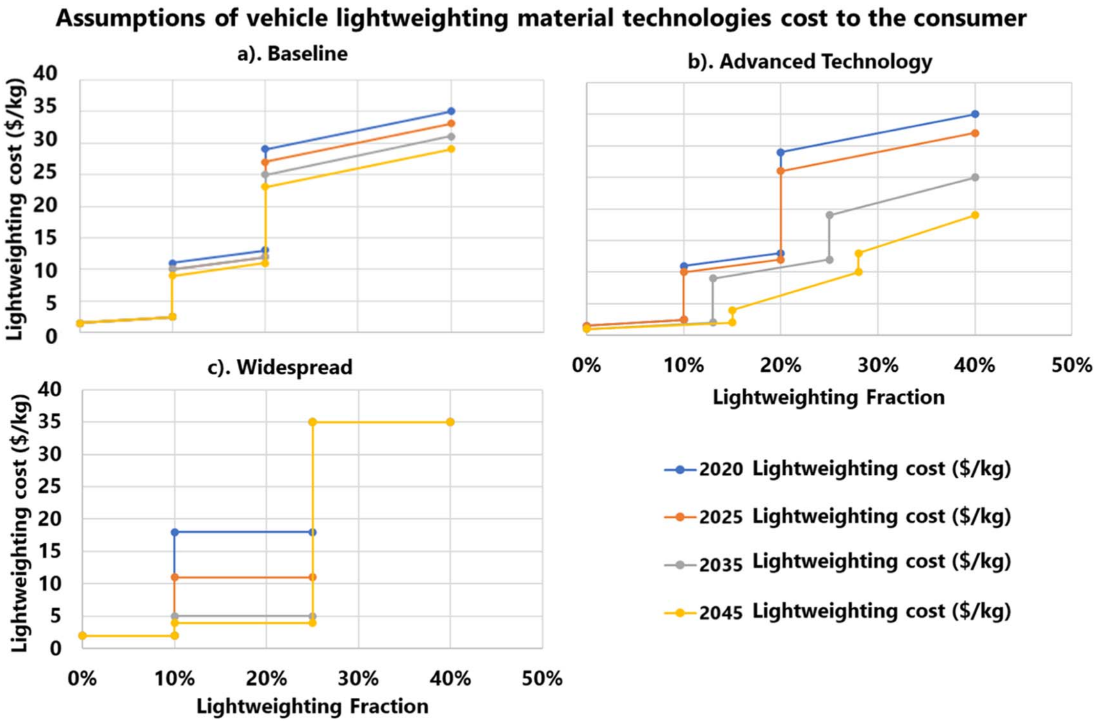


Figure 4. Assumptions of vehicle lightweighting material technologies cost to the consumer.

2.4. CAFE/GHG standards

This analysis models the influence of Corporate Average Fuel Economy (CAFE) and GHG-related regulations as described in section 2. It assumes the standards follow the Safer Affordable Fuel-Efficient (SAFE) Vehicles Rule through 2026, as shown in figure 3(b). After 2026, it follows the requirement that the standards continue to increase as long as they are feasible, the required MPG almost doubled from 2015 to 2050 for both car and trucks. Feasibility was assumed to be limited to a maximum per-vehicle incentive of $2,000. If that amount was not enough to shift sales to meet the standards, it was assumed the standards would be delayed 4 years.

2.5. Materials

The three sets of material technology cost assumptions, shown in figure 4, were provided by the Vehicle Technologies Office Materials Program in collaboration with the U.S. Driving Research and Innovation for Vehicle efficiency and Energy sustainability Materials Technology Team and were implemented in the ADOPT model to estimate the amount of lightweighting applied to new vehicles and the overall market. The first represents a baseline cost of lightweighting based on current industry trends without any additional support from the USDOE. The second, advanced technology, represents the potential reduced costs of lightweighting assuming an aggressive research and development program. The third cost model, widespread, is more simplified and represents an average cost target rather than an aggressive technology path, which, if achieved, would likely lead to significant adoption of lightweighting across the fleet.

The first set of lightweighting assumptions, the baseline scenario, has three discontinuous sloping lines that capture the increasing cost to the consumer as a function of the amount of lightweighting. The discontinuities capture the step function price changes observed by industry in integrating lightweighting technologies from low cost (nominal design improvements and advanced steels), medium cost (additional aluminum and magnesium integration), and high cost (advanced metals and composites). The lines' slopes capture how some components are less expensive to lightweight than others. Multiple lines show how lightweighting costs decrease over time. Figure 4(b) shows the scenario of advanced technology lightweighting cost to the consumer. It is similar to the baseline scenario but captures how additional research could expand how much total lightweighting could be accomplished for each cost band, as well as greater cost reductions over time within each technology band. Figure 4(c) illustrates the scenario of widespread lightweighting cost to the consumer. It is a simplified approach that was constructed based on knowledge gained by running the first two scenarios. Although the flat cost curves are less representative of actual industrial processes, this model provides an exploratory target of $5/kg lightweighting cost to the consumer in 2035 to assess the potential impact. It represents a cost target rather than an aggressive technology path, which, if achieved, would likely lead to significant adoption of lightweighting across the fleet.

3. Approach

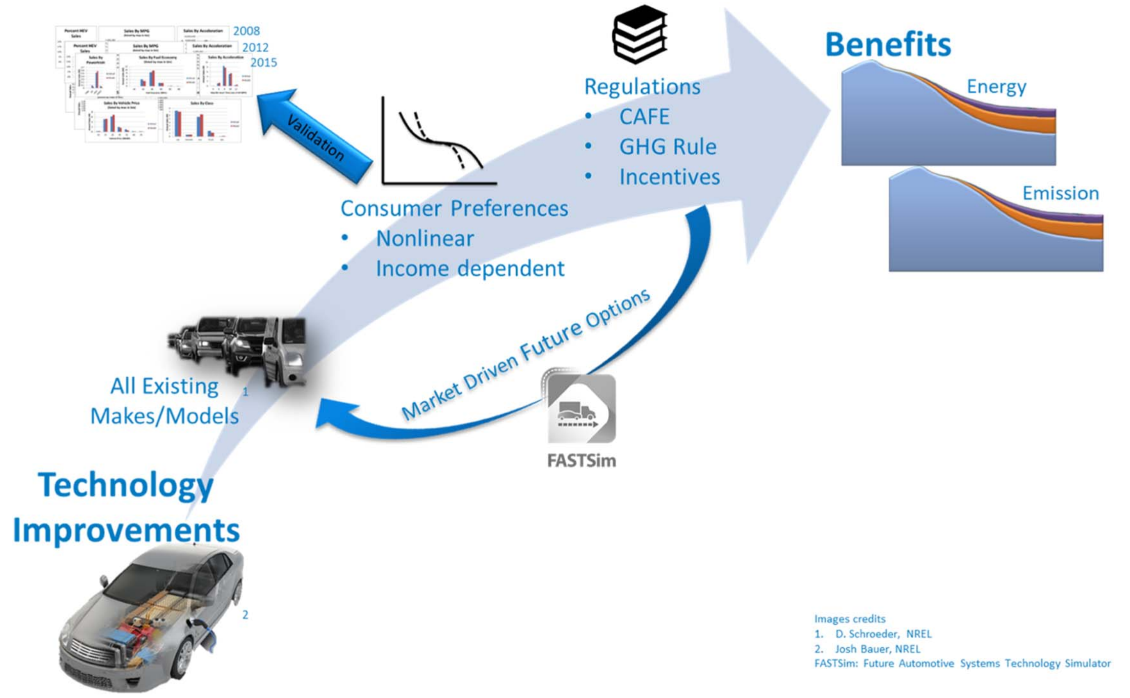
The ADOPT [25] was used to address previous analysis gaps. It estimates how much lightweighting is used on different vehicles by combining a consumer choice model with cost Versus weight reduction relationships. The cost of lightweighting is represented by a series of cost curves that provide the overall increase in vehicle cost ($/kg) per percent of vehicle weight reduction. Three scenarios are investigated in this analysis: baseline, advanced technology, and widespread adoption scenarios. The fleet-level market penetration, lightweighting fraction, and GHG emissions of each scenario are investigated to provide insight for suitable lightweighting cost targets to maximize the benefits.

ADOPT estimated the GHG emissions impact of material lightweighting on the light-duty fleet. ADOPT is a vehicle choice and stock model that estimates the impact of vehicle technology improvements on sales, energy, and GHG emissions, as shown in figure 5. Simulations start with the over 700 existing vehicle makes, models, and options. This provides realism, captures any outlier characteristics of the best-selling advanced vehicles, and enables regulation influences to be modeled. Sales among the vehicles are estimated based on their attributes including price, fuel cost per mile, acceleration, size, and range.

$$S_V = \frac{\mathrm{EXP}\left(\sum_A (E_A \times V_A)\right)^x}{\sum_V \left(\mathrm{EXP}\left(\sum_A (E_A \times V_A)\right)^x\right)} \tag{1}$$

Equation (1). represents the factors influencing the market share (S_V) of a specific vehicle model (V) [11]. where, EA indicates the coefficient associated with a particular attribute (A); VA represents value of that attribute A for the vehicle (V). Additionally, there is a sales distribution factor x that affects the overall sales distribution of the vehicle model. Those attributes are valued nonlinearly across their range and as a function of consumer income.

For example, differences in acceleration are more important for very quick or very slow accelerating vehicles, and acceleration importance increases for high-income households. This approach enables ADOPT to match historical sales in many dimensions and across multiple years. The consumer preferences are also used to create new future vehicle options based on market conditions using the integrated Future Automotive Systems Technology Simulator (FASTSim) vehicle powertrain model [26]. Using an optimization routine, ADOPT sends FASTSim different component sizes, such as engine or battery size, and gets back vehicle attributes, including efficiency and acceleration. It then uses those attributes to estimate sales and find the best component sizes. This leads to market-driven vehicle options. Similarly, ADOPT optimizes the level of lightweighting for each vehicle over time. It tries different levels of lightweighting, which impacts purchase price, fuel cost, and acceleration, until it maximizes sales demand. This approach leads to market-driven component sizing and lightweighting. For instance, as battery prices decrease, ADOPT tends to create battery-electric vehicles with larger batteries that provide longer range and better acceleration. Similarly, as lightweighting costs decrease, the amount of lightweighting tends to increase. The sales estimates feed into a stock model that tracks sales, miles traveled, and survival of vehicles to quantify energy consumption and GHG emissions. The vehicle stock is estimated using a non-linear vehicle turnover model based on trends from the Transportation Energy Data Book, which is also adjusted to capture the increasing median vehicle age that has grown by over 50% since 1970.



Images credits
1. D. Schroeder, NREL
2. Josh Bauer, NREL
FASTSim: Future Automotive Systems Technology Simulator

Figure 5. Overview of the ADOPT model. FASTSim: Future Automotive Systems Technology Simulator.

The ADOPT program incorporates how CAFE standards and GHG standards (as presented in figure 5) affect technology adoption. As shown in figure 1, technology improvements were used to improve size and performance instead of efficiency while the standards were held constant. ADOPT could capture the influence of standards using incentives and penalties. Price penalties are applied to vehicles that fall short of the standards, proportionally to how far they fall short. Similarly, incentives are applied to vehicles that exceed the standards, proportionally to how far they exceed them. The penalty and incentive rates are solved such that the penalties pay for the incentives.

ADOPT also models how CAFE and GHG-related standards increase in the future, as illustrated in figure 5. Federal law requires fuel economy standards to be set at the maximum feasible level [27]. ADOPT captures this by using the assumption that the fuel economy standards increase. It then uses a prescribed maximum incentive to determine feasibility. If the maximum incentive is not enough to shift sales to meet regulations, the regulation increase is delayed for a prescribed period. The incentives and penalties from the regulations influence the estimated amount of lightweighting applied. ADOPT optimizes the amount of lightweighting to maximize the estimated sales demand, trading off the additional cost of lightweighting with the change in incentives and penalties gained by efficiency improvements of lightweighting.

To summarize, ADOPT emphasizes the importance of vehicle attributes in predicting sales, rather than relying solely on the number of make and model options [12, 13]. This approach allows for a more accurate reflection of consumer preferences and decision-making processes. ADOPT validates its projections using historical sales data, ensuring that the model's predictions are grounded in real-world market trends [23]. Moreover, ADOPT's predictions incorporate a wider array of factors when forecasting vehicle sales, facilitating a more thorough and nuanced interpretation of market dynamics [14, 15]. This comprehensive approach makes ADOPT's forecasts more reliable and accurate [14, 16, 17]. Thus, in order to estimate the cost of lightweighting required to achieve significant adoption of light-duty vehicles and achieve reductions in energy consumption and greenhouse gas (GHG) emissions, three distinct scenarios (baseline, advanced technology, and widespread) for the cost of lightweighting in the U.S. market have been evaluated using ADOPT in this analysis.

4. Results

Three different costs of lightweighting scenarios (baseline, advanced technology, and widespread) are evaluated employing ADOPT in the U.S. market. The evaluation involved analyzing the detailed sales of various vehicle models and types within each scenario. The result section covers US light duty vehicle (LDV) market composition and the corresponding energy consumption and greenhouse gas (GHG) emissions, considering the sales data and relevant vehicle parameters. To gain a deeper understanding of the impacts of different

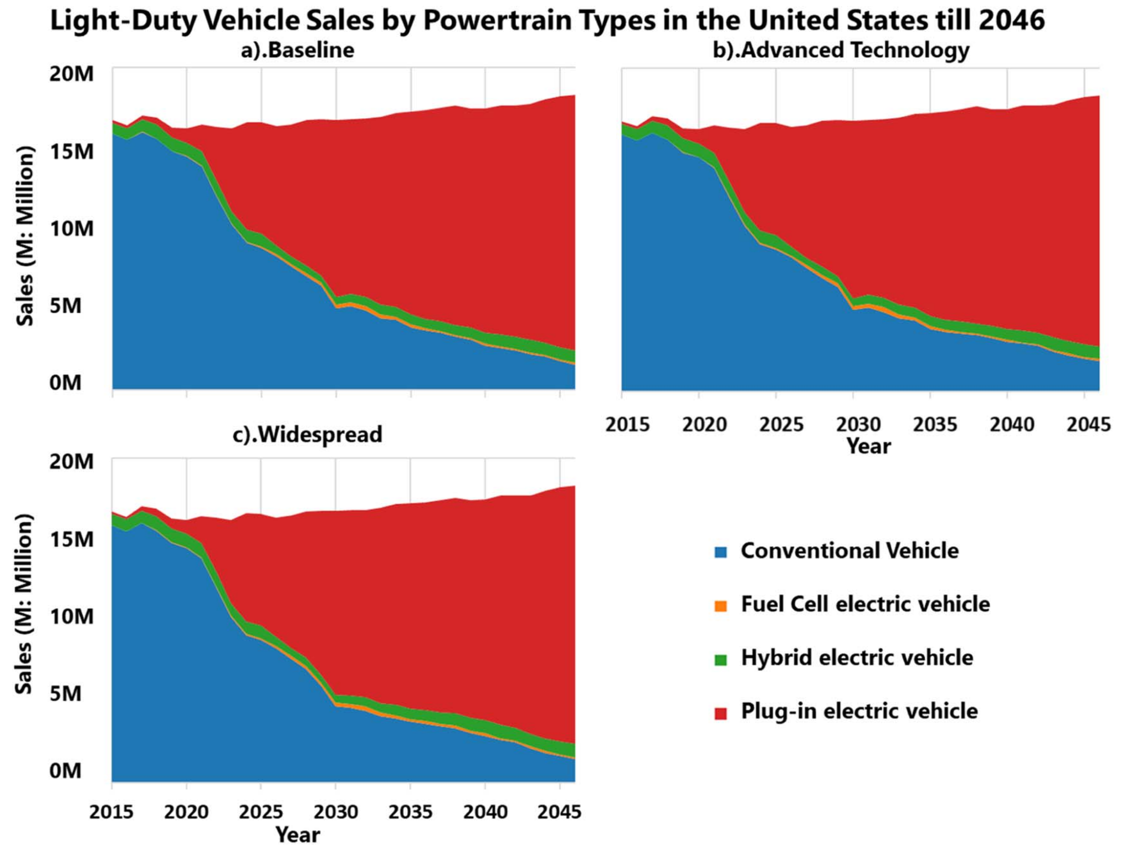


Figure 6. LDV sales by powertrain.

lightweighting materials, this section also provided and interpreted the detailed lightweighting fraction and sales data. These insights were crucial in explaining why and how these impacts were generated and operated within the light-duty vehicle market.

Figure 6 presents the LDV sales by powertrain of three scenarios. It indicates that the assumptions in the baseline scenario include enough technology progress and the right market conditions to change powertrain sales from primarily conventional gasoline to plug-in electric vehicles (PEVs: including both Battery Electric Vehicles (BEVs) and Plug-in Hybrid Electric Vehicles (PHEVs)). PEV sales increase from 5% in 2020 to 66% in 2030. Then, with decreasing battery prices, PEV sales continually increase to 87% in 2046. At the same time, with the increase of renewable powertrain vehicles, conventional vehicle sales drop 90% from 2015 to 2046. For all scenarios, the general sales trends were similar. These results suggest that in all three lightweighting scenarios, the sales by powertrain remain largely unchanged, which further indicates that the use of lightweighting materials does not have a significant impact on sales of different powertrains.

Combining the annual powertrain vehicle sales with the existing fleet size and their unit petroleum consumption and GHG emissions (use-phase), the annual LDV petroleum consumption and GHG emissions are calculated and presented in figure 7.

Petroleum consumption and GHG emissions reduce from 8.3 million barrels per day (MBPD) and 1,394.4 million metric tons (MMT) in 2015 to 2.06 MBPD and 588.5 MMT in 2046. Conventional vehicles account for almost all the petroleum consumption and GHG emissions reductions in the early stage. Starting in 2023, the share of PEVs increases and reaches 14% in 2040, for about 0.4 MBPD. GHG emissions show similar trends in the reduction of conventional vehicles and increase of PEV powertrains.

Given that lightweighting costs have a minimal effect on sales and market share across different powertrains, the resulting impact on energy consumption and greenhouse gas (GHG) emissions from a powertrain perspective would also be limited. To delve deeper into the market's response to lightweighting costs, we present below a breakdown of the lightweight fraction at various vehicle prices for all three scenarios. This analysis aims to emphasize the specific effects of the cost of lightweighting materials within the three scenarios.

Figure 8 presents the baseline scenario lightweighting fraction and sales by vehicle price. The thickness of the lines corresponds to the sales volume of vehicles at specific price points. It is evident that while certain vehicles (>=$100 K) exhibit significant lightweighting (more than 40%), their sales remain limited. The majority of vehicles sold exhibit moderate levels (10%-20%) of lightweighting.

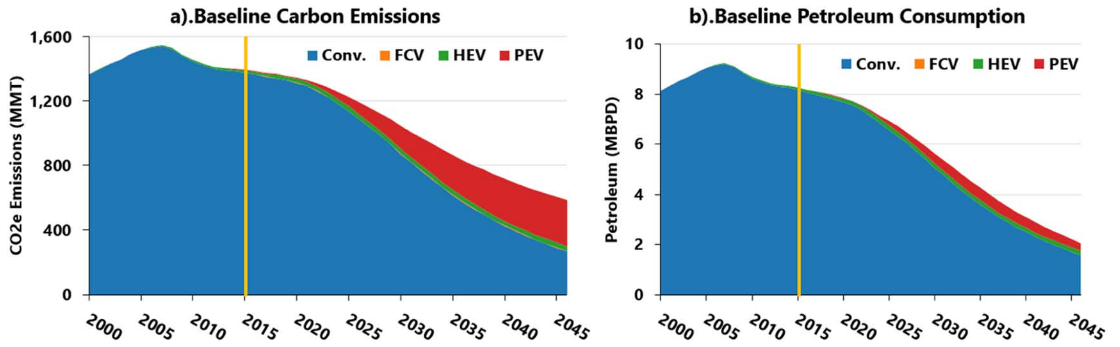


Figure 7. Baseline petroleum consumption and GHG emissions (use-phase) of LDVs. (FCV: fuel cell electric vehicle; HEV: hybrid electric vehicle; PEVs: plug-in electric vehicles).

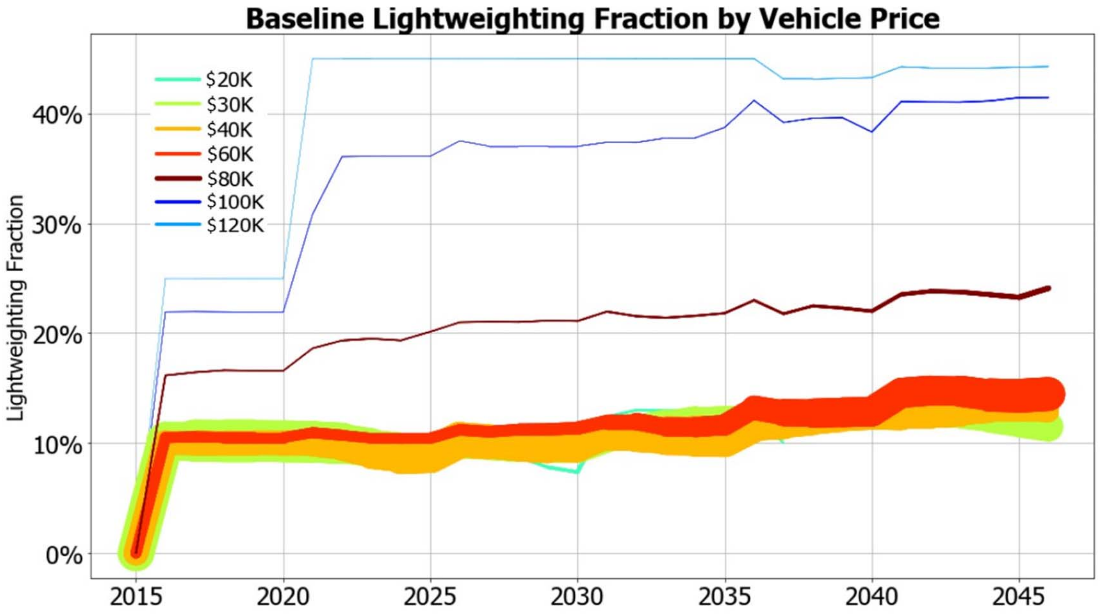


Figure 8. Baseline lightweighting fraction and sales by price of the LDV market; *y*-axis is the lightweighting fraction, and the line thickness represents sales. $20 K: $0-$20 K, $30 K: $20K-$30 K, $40 K: $30K-$40 K, $60 K: $40K-$60 K, $80 K: $60K-$80 K, $100 K: $80K-$100 K, $120 K: $100K-$120 K.

Figure 8 shows that lightweighting corresponds with vehicle price, where high-price vehicles adopt a high lightweighting fraction; the lightweighting fraction of the $120,000 vehicles is about 45%. The $100,000 vehicles rise to more than 35% of the lightweighting fraction. For $80,000 vehicles, the lightweighting fraction is around 20% in 2046. For the lower-price vehicles, such as $20,000–$40,000, the lightweighting fractions are 10% in 2046. Meanwhile, comparing the sales of vehicles of different prices, the high-price vehicles only account for a small fraction of the overall market sales. The total sales of $100,000 and $120,000 vehicles only account for 2% of the overall LDV sales in the United States in 2046. The $30,000, $40,000, and $60,000 vehicles together account for more than 90% of the market share; however, the lightweighting fractions for vehicles in these price ranges are only about 10% through 2040. Thus, the lightweighting fraction of the overall LDV market is still relatively small (around 14%) in 2046 due to the dominant market share of lower-price vehicles.

The advanced technology scenario explored lower-priced lightweighting, which increases lightweighting adoption and benefits. Figure 9 shows the advanced technology lightweighting fraction and vehicle sales by price, which indicates an increase in the lightweighting fraction of middle-price vehicles. There is little difference between the advanced technology and baseline scenario cost inputs for 2020 and 2025, which results in no change to the lightweighting of the fleet. Then, starting in 2035, the lightweighting increases for all vehicles with a price less than $100,000 due to their sensitivity to lightweighting material price, which is less than $2/kg for the 0%–13% lightweighting and less than $10/kg for the 13%–16% lightweighting. Thus, in order to represent a widespread scenario, $5/kg is proposed for the 10%–30% lightweighting due to the high adoption rate at the

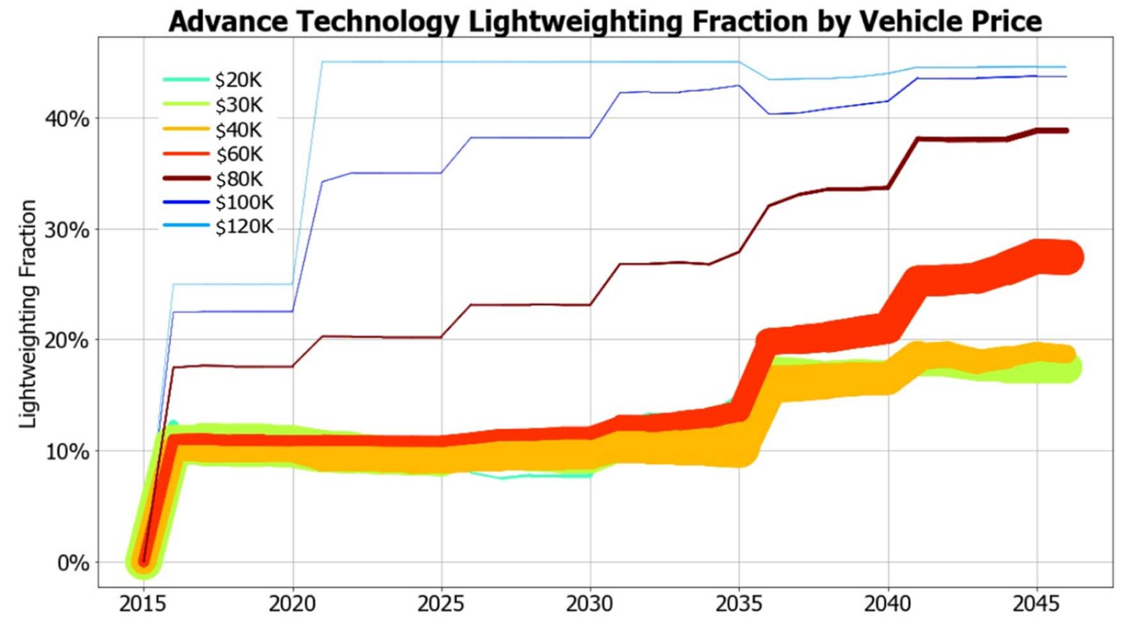


Figure 9. Advanced technology lightweighting fraction and sales by price of the LDV market; *y*-axis is the lightweighting fraction, and the line thickness represents sales.

price range in both the baseline and advanced technology scenarios. The lightweighting fraction of $80,000 vehicles increases to about 40% in 2046, which is 15% higher than the 25% in the baseline scenario. Furthermore, the lightweighting fraction of the $20,000–$40,000 vehicles increase to about 15%, and the $60,000 vehicles increase to 25%–30% in 2046. Considering the significant share (more than 50% of lower-price [$20,000–$40,000] vehicles), the lightweighting fraction of the LDV market increases. Comparing the difference between baseline and advanced technology scenarios, we could find that for $80,000 vehicles, the lightweighting material could be widely applied around the price of $20/kg.

For the advanced technology LDV sales by price—in line with the baseline scenario—$30,000, $40,000, and $60,000 vehicles still take more than 90% share of the LDV market. Thus, the lightweighting fraction in the market increases after 2030 due to the increased lightweighting fraction of the $30,000, $40,000, and $60,000 vehicles.

Because there was still limited lightweighting under the advanced technology lightweighting material price assumptions for $30,000 and $40,000 vehicles, we changed the target and increased benefits to apply more lightweighting technologies at a faster speed in the widespread scenario. The lightweighting fraction and sales by price range of the LDVs of the widespread scenario are presented in figure 10.

The widespread scenario was designed to have greater market adoption and energy and emissions benefits. For simplicity and effectiveness, it was constructed with constant prices with discontinuous changes at 10% and 25% lightweighting fraction, as shown in figure 4. This end-target price level was set to correspond with high levels of market adoption in lower-price bins. For high-price vehicles, a lower price limit would not increase the lightweighting fraction any more due to their insensitivity to lightweighting material cost. Another interesting finding is that the $11/kg price could increase the lightweighting fraction of $80,000 vehicles. Last and most important, $5/kg is a crucial cutoff price for lower-price vehicles to widely adopt lightweighting. Thus, the widespread scenario could increase the lightweighting fraction of the lower-price vehicles to 25% starting in 2035. For the widespread LDV scenario, the $30,000–$60,000 vehicles take most of the market share. Accordingly, the overall market lightweighting fraction is larger than 25%.

Figures 8–10 collectively illustrate that the majority of the light-duty vehicle market, particularly vehicles priced between $20,000 and $60,000, exhibit a high degree of price sensitivity. Consequently, the extent to which the overall market can adopt lightweighting technologies is heavily dependent on the cost of lightweight materials. The lower the cost of these materials, the higher the potential for widespread adoption of lightweighting across the market. The analysis reveals that a price point of $5/kg represents a critical threshold, below which lower-priced vehicles can feasibly incorporate lightweighting technologies on a broad scale. This underscores the importance of reducing the cost of lightweight materials to facilitate their widespread implementation in the light-duty vehicle sector.

As mentioned previously, some benefits went to performance rather than efficiency. Figure 11(a) shows the improvement in the acceleration time of both the advanced technology and widespread scenarios compared to

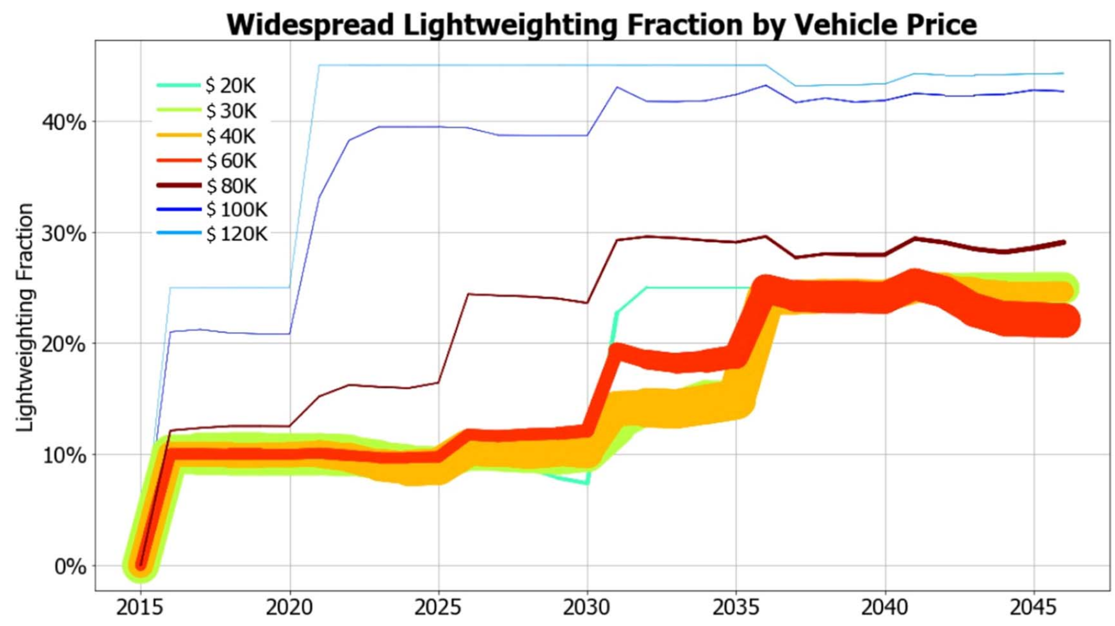


Figure 10. Widespread lightweighting fraction and sales by price of the LDV market; *y*-axis is the lightweighting fraction, and the line thickness represents sales.

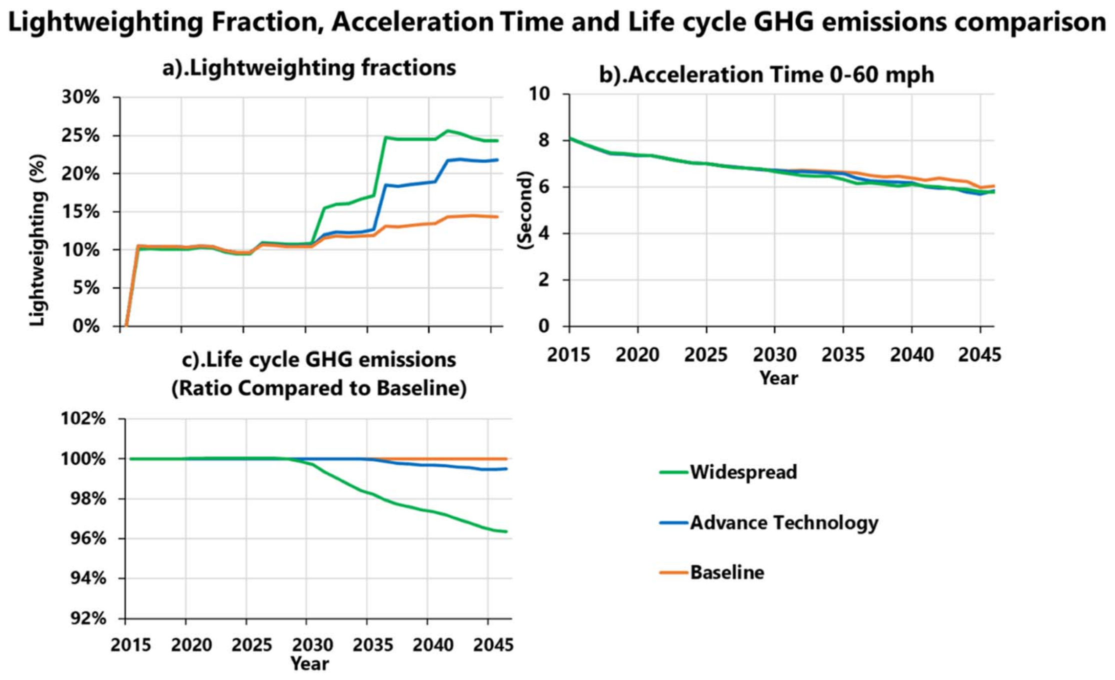


Figure 11. Lightweighting fraction, acceleration time and life cycle GHG emissions comparison of the three proposed scenarios.

the baseline scenario. Combining the vehicle sales and corresponding vehicle efficiencies, the fleetwide life cycle GHG emissions benefits are calculated and presented in figure 11(b). A 4% reduction corresponds to a reduction of more than 22 MMT CO_2 equivalent. In the advanced technology scenario, the fleet-wide lightweighting fractions could be significantly increased (more than 5%), but the majority of these benefits were realized in terms of performance, specifically acceleration. Consequently, the GHG emissions benefits in the advanced technology scenario are limited compared to the baseline scenario. In contrast, under the widespread scenario, the acceleration performance remains relatively stable. The majority of the lightweighting benefits (2%–3% lightweighting fractions) are seen in vehicle efficiency, resulting in a significant decrease in life cycle GHG emissions. This emphasizes the advantages ADOPT model, which considering a wider array of factors when forecasting vehicle sales, as it enables a more comprehensive and nuanced interpretation of market dynamics.

5. Conclusions

The findings of this study indicate significant potential GHG emissions benefits from material lightweighting in the US light-duty vehicle fleet. The 'widespread' scenario, where the cost of lightweighting in 2035 was as low as \$5/kg, increased lightweighting adoption to 25% with a strong emphasis on middle-priced and lower-priced vehicles ranging from \$0 to \$80 K. This impact is estimated to result in a 4% reduction in GHG emissions, which translates to approximately 22 million metric tons of CO_2 equivalent in one year (2046).

By recognizing the inherent potential in material lightweighting cost to the adoption of lightweighing fraction and further the vehicle and environmental performance improvement, it is critical to account for market dynamics and consumer preferences, focusing on the formulation of strategies that harmonize the uptake of lightweighting technology with both market demands and environmental goals. While acknowledging the trade-off between production and use emissions in lightweighting strategies, this study primarily considers operational GHG emissions. This focus helps reduce uncertainties associated with variable material production and complex supply chains, offering targeted insights for US market stakeholders. Future discussions could benefit from a focus on how policy environments might evolve to better capitalize on minimizing the costs and GHG emissions associated with lightweighting materials. Stakeholders are encouraged to engage with these findings in their deliberations on policy development and implementation strategies, keeping in mind the broader goal of GHG reduction through lightweighting cost reduction.

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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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