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Green Principles for Vehicle Lightweighting

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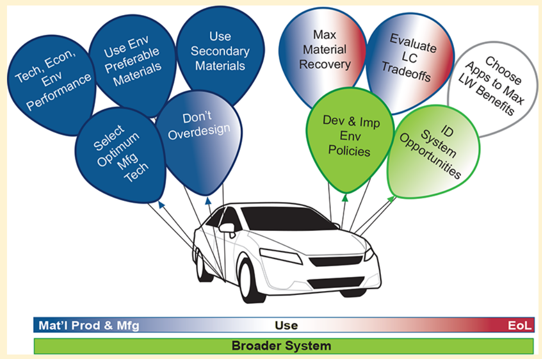
ABSTRACT: A large portion of life cycle transportation impacts occur during vehicle operation, and key improvement strategies include increasing powertrain efficiency, vehicle electrification, and lightweighting vehicles by reducing their mass. The potential energy benefits of vehicle lightweighting are large, given that 29.5 EJ was used in all modes of U.S. transportation in 2016, and roughly half of the energy spent in wheeled transportation and the majority of energy spent in aircraft is used to move vehicle mass. We collect and review previous work on lightweighting, identify key parameters affecting vehicle environmental performance (e.g., vehicle mode, fuel type, material type, and recyclability), and propose a set of 10 principles, with examples, to guide environmental improvement of vehicle systems through lightweighting. These principles, based on a life cycle perspective and taken as a set, allow a wide range of stakeholders (designers, policy-makers, and vehicle manufacturers and their material and component suppliers) to evaluate the trade-offs inherent in these complex systems. This set of principles can be used to evaluate trade-offs between impact categories and to help avoid shifting of burdens to other life cycle phases in the process of improving use-phase environmental performance.



■ INTRODUCTION

Studies on transportation vehicles (cars, trucks, buses, trains, airplanes, ships) have found that the bulk of the impacts over a vehicle's life cycle occur in the use phase (vehicle operation), so improving vehicle life cycle environmental performance should focus first on reducing use-phase burdens.[1] Fuel economy regulations in the U.S. have helped drive technological advancements to reduce use-phase impacts of individual vehicles.[2] These advancements include improved powertrains (high-efficiency internal combustion, electric, and hybrid)[3−7] and vehicle mass reduction (lightweighting).[8−12] Vehicle fuel consumption comprises two components, one associated with moving the mass of the vehicle and one that accounts for other losses (e.g., aerodynamic drag, accessories, engine, and powertrain friction).[10,13−16] Up to 50% of a wheeled vehicle's fuel consumption can be mass-dependent, depending on the vehicle type and duty cycle, so lightweighting strategies are of high value in reducing use-phase fuel consumption. Vehicle lightweighting provides the opportunity to reduce use-phase fuel consumption further through secondary mass reduction and powertrain adaptation and resizing.

Lightweighting can be achieved in several ways, with material substitution and changes in design and construction being the most common.[4,5,8,17−20] Substitution ratios that indicate the amount of lightweight (LW) material used to replace an existing material (e.g., aluminum for steel) have been developed for a range of applications and materials.[12,21,22] An alternative approach advocates making vehicle parts using near-net-shape manufacturing pathways to reduce waste of existing materials.[23−27] The Appendix to the Midterm Evaluation of Light-Duty Vehicle Greenhouse Gas Emission Standards and Corporate Average Fuel Economy Standards for Model Years 2022−2025 lists a number of mass reduction technologies for materials such as steel and aluminum as well as lightweighting implementation examples like Ford Motor Company's aluminum-intensive F150.[28] Although material substitution and other lightweighting approaches can reduce use-phase energy consumption and GHG emissions, they often result in higher burdens in other life cycle phases. For example,

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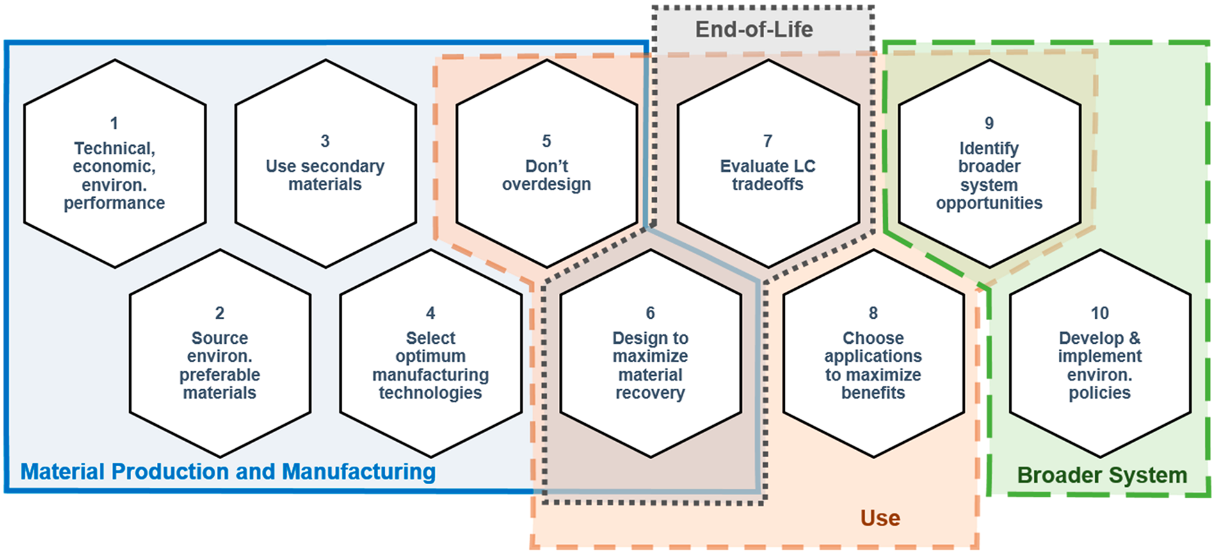

Figure 1. Vehicle lightweighting green principles framework.

an aluminum part reduces use-phase fuel consumption compared to a functionally equivalent steel part, but it takes significantly more energy to produce virgin aluminum (135.3 MJ/kg) than virgin steel (35.3 MJ/kg).[29] Manufacturing burdens differ between materials,[30] but it is also critical to understand how mechanical and structural properties of materials influence factors such as durability and part replacement frequency.[31−34] The recoverability of a material at the end of a vehicle's lifetime is another important criterion, as it is desirable to keep materials in functional uses once they have been produced and to reduce waste. Recyclability depends on material properties, ability to separate materials at end-of-life, and the amount and type of contamination present after separation. Lightweight material selection and design to reduce life cycle environmental impact is complicated and involves evaluating trade-offs.

One of the first comprehensive methods for quantifying the environmental performance of products across their entire life cycles (i.e., from cradle to grave) was developed by a panel of industry, regulatory, and academic stakeholders.[35] This method—life cycle assessment (LCA)—was standardized as ISO 14040 in 1998 and 2000 and updated in 2006.[36] The LCA method is used to develop environmental product declarations (EPDs) according to product category rules (PCRs) under ISO 14025.[37] Partly through the application of LCA, it became evident that the process of improving environmental performance of a product across its life cycle often involved evaluation of material production burdens and trade-offs between life cycle phases as well as determination of how to account for recycled material. LCA provides guidance for navigating the complex product environmental improvement process but itself involves significant data collection and analysis effort. The objective of this paper is to establish a set of principles based on a life cycle framework to guide lightweighting technology development and application in material selection, vehicle design, and policy.

■ PRINCIPLES BACKGROUND

Sets of principles, based on LCA concepts, data, methods, and applied experience, are intended to simplify and guide the environmental improvement process and have been developed in several fields. Anastas and Warner developed a set of principles tailored specifically for green chemistry,[38] and Anastas and Zimmerman continued with 12 Principles for Green Engineering.[39] Examples of principles from these sets include: use renewable materials; reduce waste; use less toxic materials; and design for durability. The American Institute of Chemical Engineers consolidated these principles into a set of nine focused on implementation[40] and continued the consolidation with a set of four principles. This would be an academic exercise if these principles had not been adopted and put into practice by practitioners who understood their value. Two examples of adoption are Dow Chemical's corporate sustainability goals[41−43] and BASF's selection of environmental categories for their eco-efficiency analysis.[44,45]

Green principles have been developed for other engineering disciplines. The Hannover Principles focused on design for sustainability,[46] and the Sandestin Conference principles were the product of an effort to provide a set of green engineering principles applicable to all engineering disciplines.[40] A recent set of principles focuses on the development and deployment of energy storage on the electricity grid,[47] and these principles have been recognized as an important contribution to the design of battery technologies.[48,49]

Principles collect, distill, and organize information in a topic area to provide useful guidance to those who are making design and deployment decisions. Many economic aspects are currently internalized in decision-making processes, so principles are of the highest value when they focus on aspects, especially environmental and social, that are not yet internalized. Externalities such as greenhouse gas emissions are one example. Material selection[50] and lightweight (LW) design[51] have both been the subject of work to develop multiobjective frameworks for decision-making that include cost, performance, and environmental factors. We present here a set of 10 principles, and an organizing framework, focused on guiding the environmental improvement of transportation vehicle systems (including, but not limited to, passenger cars, trucks, trains, ships, and planes) through lightweighting.

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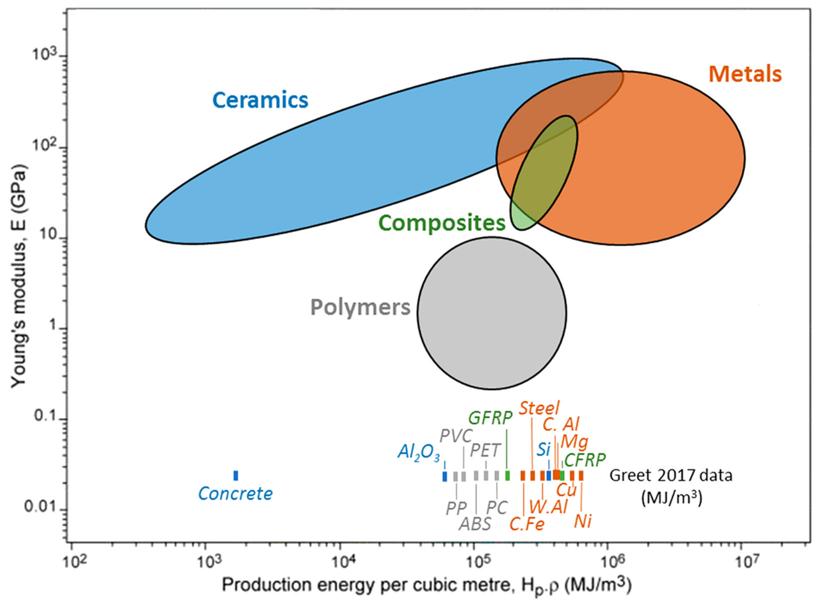

Figure 2. Ashby chart (see ref 60) depicting production energy versus Young's modulus for several material types, using material production energy data from ref 29.

LIGHTWEIGHTING PRINCIPLES FRAMEWORK

The principles framework (Figure 1) illustrates the relationship between the 10 principles and product life cycle phases (material production, manufacturing, use, and end-of-life). The principles are intended for multiple stakeholders, including designers, vehicle manufacturers (OEMs), the supply chain for these manufacturers (i.e., materials and component suppliers), and policy-makers.

Though these lightweighting principles are focused on the environmental dimension of sustainability, they have economic and social components too. For example, a principle focused on reducing energy use will also have an effect on the economic performance of a product or system. In addition to the trade-off between material production and use phases, there are also potential trade-offs between other life cycle phases, between stakeholders' interests, and between part, vehicle, fleet, and transportation system scales. These principles, employed as a holistic set to evaluate performance and resolve trade-offs, provide consistent and systematic guidance on lightweighting strategies to minimize life cycle environmental impacts of the vehicle system.

LIGHTWEIGHTING PRINCIPLES

Each of the 10 environmental principles for vehicle lightweighting are discussed below, in both short (**bold**) and more explanatory form (*italics*), with background and illustrative examples for each as well as candidate tools and metrics to quantify improvement for that principle and to identify potential gaps in current practice.

Principle 1: Resolve Trade-Offs between Technical, Economic, and Environmental Performance. *Successful and high-impact lightweighting strategies must resolve trade-offs between technical, economic, and environmental performance while maintaining safety standards.*

Lightweighting initiatives to improve environmental performance can result in increased production costs and/or decreased technical performance and can also affect cost of vehicle ownership.[52] For example, although magnesium is a candidate for LW designs because of its low density, its cost has traditionally been prohibitive in designs for automotive applications, and its corrosive nature has limited its use in the aerospace industry.[53,54] Material cost issues can be addressed by designing specifically for LW applications, reducing the amount of material required by near-net-shape applications and keeping costs low, and by employing efficient, low-cost manufacturing.[53] In the case of magnesium, new cast and wrought alloys with better mechanical and corrosion properties are required for implementation to expand.[54,55] The introduction of LW materials into vehicle designs also introduces technical issues related to LW material forming and joining. For example, although aluminum has one-third the density of steel, it also has one-third the strength and tensile modulus.[56] To counteract this lower tensile modulus, a larger hollow cross section must be formed, or part thickness must be increased. Many LW alloys require harder tools and more rigid presses, and their lower ductility limits design options.[56] Joining dissimilar materials, often necessary when designing with LW materials, can be challenging due to weaker connection points and dissimilar physical and chemical properties.[57,58] Alternatives to traditional resistance and arc welding techniques include joining by forming, stir and inertia friction welding,[56] and emerging reversible adhesive bonding technology. Joining is discussed further in Principle 6.

Metrics, Tools, and Gaps in Practice. Despite the challenges associated with LW materials, they offer a promising path to reduce environmental burdens in transportation vehicle designs. Ashby charts, which display the range of selected properties for a variety of materials, can be a helpful tool in comparing candidate materials.[59] Figure 2 is a schematic adaptation of an Ashby chart, displaying ranges of production energy (per m^3) and Young's modulus for several broad material types[60] as well as material production energy data points from GREET for some selected materials.[29] Ashby charts help designers select LW materials with the best environmental performance that also maintain specified material properties. Other metrics that could be displayed in

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an Ashby chart include the cost, energy density, GHG emissions factor, and mass.

Vehicle designers need to have adequate information, experience, and tools (e.g., finite element models and testing facilities) to assess whether the part made from an alternative material will meet vehicle structural and safety requirements. Potential data gaps include material substitution factors,[61] durability, and life cycle inventory data that are needed for the cradle-to-gate life cycle inventory (LCI). These data are also especially important for Principle 7. Exploring several alternative lower-density materials for an application can help identify the "right" material when resolving trade-offs (Principle 7).

Principle 2: Source Abundant and Low-Environmental-Impact Materials. *Choose to use materials that are abundant and use lower-impact material production energy sources.*

The global abundance and geographic origin of materials influences the environmental sustainability of products and systems in which they are used. Steel and aluminum are currently two of the most common materials (by mass) in transportation vehicles, and both of them are abundant. Some predict that society's access to aluminum will be constrained by energy limitations and price before scarcity,[62] though many (non-lightweight) materials used in vehicles, such as copper, lead, and zinc, are far less abundant.[63] Scarcity of cobalt, a critical material in magnets, aircraft engines, turbines, cutting tools, and batteries, is a concern due to potentially widespread impacts.[64,65] Lightweighting will become an even more important strategy as more electric vehicles are produced, because battery performance is directly related to the amount of mass being moved. Demand for battery materials (e.g., lithium) will also increase. Concerns have been raised regarding the abundance of lithium,[66,67] but several studies indicate that the demand for lithium batteries can be supported for decades.[68−70] LW materials are often more scarce than traditional metals. Magnesium's price and availability has limited its use as an LW material,[71,72] and there is also concern in the automotive industry regarding the scarcity of rare-earth elements.[73]

Some studies argue that resource scarcity is less of a problem than resource extraction,[74,75] which has been shown to have the largest environmental impact in the product supply chain.[76] Extraction and processing of scarce materials causes negative environmental impacts, such as high energy consumption, toxic emissions, and ecosystem degradation,[30,77−79] and resource depletion exacerbates these impacts, as it typically requires extraction from lower and lower ore grades.

In addition to raw materials, sources of energy also need to be considered. Energy used in extraction and processing is a primary cause of environmental impact associated with materials, and fossil fuels are still the dominant energy source for this activity.[80] As a result of regional differences in the mix of fuels used to produce electricity in the U.S., GHG emissions per kg of aluminum ingot vary between 5 and 30 kg of CO_2e depending on production location.[81] Energy and GHG emissions from producing virgin aluminum will also vary over time as the grid mix evolves.[82] Although many LCAs currently assume that aluminum is being produced in North America, where hydroelectric-powered production is common, and thus, GHG emissions are lower, industry experts state that Chinese aluminum production, which is primarily coal-powered, is becoming increasingly relevant, accounting for 65% of global aluminum production capacity.[61] This influences the production burdens of vehicles that use appreciable amounts of aluminum. Processing methods and associated energy and emissions burdens also vary with source ore type, which varies geographically. Variance in SO_x emissions resulting from extraction and processing of different nickel ores in Canada and Russia is an example of this spatial variation.[83]

Metrics, Tools, and Gaps in Practice. The reserves-to-production ratio, which indicates the anticipated lifetime of a nonrenewable resource, characterizes material scarcity. Comparing the reserves-to-production ratio of bauxite (100 years) to copper (42 years), it is evident that aluminum is more abundant at current production rates.[63] Material production energy (MJ/kg) is used to ensure the lowest impact energy sources are being chosen. Although databases such as GREET (Greenhouse gases, Regulated Emissions, and Energy use in Transportation)[29] report energy and emissions factors for a range of materials, data are not always available for newer and less common materials. Resource depletion (RD) is an established life cycle impact category that has several issues, including significant variation in characterization methods (over 20 different methods) and the lack of an included recycling framework, both of which are gaps in practice. Alonso et al. describe material depletion metrics and potential impacts on economies, technologies, and geographies.[65] Other tools include: Sankey diagrams, which highlight material flow pathways throughout their life cycle; Ashby charts, which demonstrate trade-offs in an LW material such as abundance and density; and life cycle assessment databases and software, such as GREET, SimaPro, or GaBi.

Principle 3: Use Secondary Materials. *Secondary materials may reduce demand for virgin materials and can result in lower material production impacts (e.g., energy, GHG emissions).*

The use of secondary (i.e., scrap and recycled) materials reduces material production impacts compared with the generally higher energy, emissions, and cost for primary material production and also reduces the need for raw material production and processing.[29] Figure 3 illustrates the difference in material production energy and GHGs between primary and secondary iron, steel, and aluminum.

Secondary materials can be unsuitable for some applications. They often do not have the same material properties and

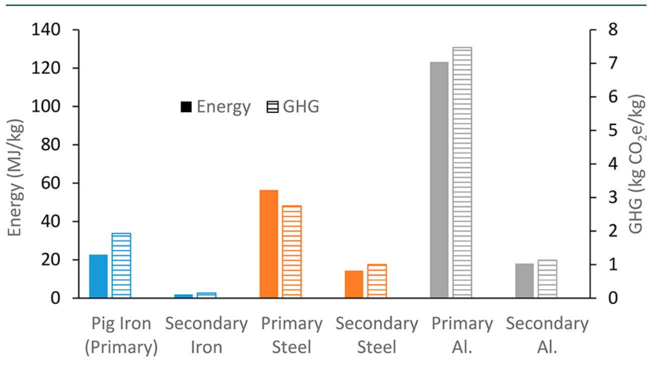

Figure 3. Reduction in material production energy and GHGs substituting primary with secondary materials—variability due to location, processing methods, etc. is not reported in GREET to ensure source confidentiality.[29]

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composition as their primary counterparts because of alloying elements and contaminants remaining after the recycling process.[61,84−88] Contamination by other elements reduces the quality of recovered materials, limiting the application of LW secondary materials, as they can often only be used in applications that accept lower-quality material.[89,90] For example, calcium, lithium, and zirconium lower the quality of magnesium,[87] and aluminum is compromised by the presence of copper, iron, or zinc.[90] Recycled plastics have not been widely used in transportation because of a lack of effective plastic recycling infrastructure and the inability to produce recycled plastic equivalent to primary material.[91,92] These end-of-life issues as well as market interactions between primary and secondary materials, will be discussed further in Principle 6.

Metrics, Tools, and Gaps in Practice. Metrics that can be used to assess performance under Principle 3 include secondary material content (%), material production energy (MJ/kg), and carbon intensity (CO_2e/kg). A higher percentage of secondary material is desirable in terms of reducing resource depletion and material production energy. Tools that can be used to facilitate improvement on Principle 3 are Sankey diagrams, which highlight how much material is being recycled for secondary use at a regional, national, or global scale, and GREET or other LCA software/material databases, which contain energy and emissions factors.

A major gap in information necessary for assessing performance under this principle is the recycled content of a material. Although the steel and aluminum industries have well-established recycling data for the automotive industry, other vehicle modes have far less information on primary and secondary material flows. For instance, ship breaking is the common end-of-life process, yet the flow of materials resulting from ship breaking is not well-documented.[93] Additionally, few technologies are capable of material recovery without compromising material quality. There is a need for recycling technologies that can accomplish material separation without detrimental contamination as well as identifying appropriate uses for secondary materials with degraded properties. The Aircraft Fleet Recycling Association (AFRA), the global organization dedicated to airplane recycling, has noted that the quality of recycled composite materials needs to improve, and expanded markets need to be identified for aircraft recycling to improve.[94] The cost and environmental burdens of future end-of-life infrastructure are unknown as is how these will influence use of secondary materials in design. Issues with end-of-life modeling and recovery of materials will be discussed further in Principle 6.

Principle 4: Maximize Efficiency in Manufacturing for Lightweight Technologies. *Develop and select environmentally preferable manufacturing technologies that have high material yields and match target production volumes.*

Material lost as scrap through the production process necessitates production of more input material than ends up in the finished product. Economics have been the primary motivation for increasing material efficiency. Barriers to implementing environmental material efficiency strategies include an industry perception that they raise costs and the lack of expert knowledge and resources.[95,96] There have been efforts to address challenges in increasing material efficiency.[97] Allwood et al.[74] discuss material efficiency as a pathway to reduce the environmental burdens of material production and processing and identify increasing process yields as one strategy.

Because manufacturing operations increase embodied energy, it is important to select manufacturing processes strategically based on target production volume to minimize burdens per part (not per kg). Fysikopoulos et al. estimated the production energy for an automotive body-in-white (BIW) at varying production volumes and found up to 17% lower energy and cost per part at higher BIW production volume.[98] Kim, Keoleian, and Skerlos demonstrate how, as production volume increases, the difference in BIW manufacturing cost between steel and aluminum reduces, with aluminum vehicles becoming more cost advantageous at higher volumes.[99] Additive manufacturing, in which parts are built up layer-by-layer to near-final shape (e.g., additive manufacturing or laser sintering), can be used to produce high-value products at low volumes with less material waste. Although additive manufacturing may not be suitable for automotive applications because of its low-volume characteristic, it is well-suited to aerospace applications. Additive manufacturing has been adopted by aircraft component manufacturers because of its capability to produce LW and cost-effective designs.[100] Additive manufacturing of components requires as little as 33% of the energy used to produce conventionally manufactured components, and the LW components could result in up to a 6.4% reduction in fuel consumption.[100] An analysis of titanium aerospace components produced by additive manufacturing determined that they used 10% of the material used in traditional (subtractive) manufacturing.[101,102] A comparison between die-casting and laser sintering methods to produce an aircraft landing gear found that, at low production volumes, sintering is more economical than die-casting when producing functionally equivalent parts.[103] Production volumes and part size vary based on vehicle mode (i.e., higher volumes for passenger cars, lower volumes for container ships), which will help determine the best manufacturing technology.

Metrics, Tools, and Gaps in Practice. Metrics to assess progress under Principle 4 include process material yield, product rejection rate, and energy intensity. Higher-process material yield and lower-product rejection or defect rate are both indicators of improved process efficiency. The production energy intensity of a part will help identify an appropriate production volume. GREET can be used for these efficiency and energy metrics. Manufacturing energy data are not always available, especially on a part or component basis or for new technologies or materials, and models to determine optimal manufacturing technology and production volumes are not available for most industries. The lack of environmental performance measurement systems (PMS) for manufacturing represents a gap in Principle 4.[104]

Principle 5: Do Not Overdesign. *Evaluate the potential increase in production burdens of strategies to extend service life and durability against fuel savings in the use phase as well as design for reasonable part lifetimes and use optimal replacement strategies to reduce environmental impacts.*

Avoiding overdesign of vehicle components is a well-established principle in both conventional and LW vehicle design, driven by economic incentives and supported by the adoption of computer-aided design and analysis to optimize vehicle parameters without the need for prototypes.[61,105−110] When extending the service life of an LW part or vehicle, a reasonable product lifetime must be considered.[111,112] For

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instance, an LW engine block that is designed to last 30 years is overdesigned for a vehicle that will be used for 15 years.[113] Optimal replacement strategies are helpful in understanding the relationship between life cycle impact and product lifetime. Although increasing vehicle lifetime does reduce the life cycle significance of production energy and emissions,[61] obsolete products "can be responsible for higher impacts during the use phase if compared with newer and more efficient products".[114] Older products that are less efficient need to be replaced to reduce environmental burdens.[115] Factors that influence a vehicle's optimal lifetime include technology improvements, vehicle deterioration with age, and regulatory factors such as Corporate Average Fuel Economy (CAFE) standards.

Extending the service life of a vehicle allows lightweighting benefits to accumulate longer. However, strategies aimed at increasing service life, like treatments to reduce rust or improve adhesion, introduce additional material production, manufacturing, and end-of-life burdens, such as the release of volatile organic compounds and increased energy demand.[116,117] For example, aircraft and marine applications of aluminum are common, but higher mechanical strength requirements compared to those of automotive applications necessitate the use of copper alloys, which reduce corrosion resistance.[118] Chromic acid anodizing of aluminum helps to reduce corrosion, but chromates are environmentally toxic, and this trade-off between strength, corrosion resistance, and the use of toxins must be evaluated.[118,119]

Metrics, Tools, and Gaps in Practice. Metrics that can be used to assess progress on Principle 5 include the design life of the part, durability, and remanufacturability. If design life of the part is greater than the design life of the vehicle, then designs with a shorter design life should be considered to reduce unnecessary part production burdens. Although durability metrics are not well-established, the European Commission Joint Research Centre (JRC) has developed a durability index.[114] This extensive approach accounts for reusability/recyclability/recoverability, recycled content, use of relevant resources, use of hazardous substances, and durability. A tool to assess durability is the Goodman diagram, which plots alternating versus mean stress to indicate likelihood of failure.[34,120] A simpler approach to evaluate the environmental benefit of a part with extended service life is to compute changes in life cycle energy or GHG emissions of the vehicle because of one more or one fewer replacement parts.

If specific components have longer life spans than the vehicle, remanufacturing can be considered to reduce resource depletion and extend service life.[121] In principle, a remanufacturability credit could be included in vehicle life cycle calculations. Tracking remanufactured parts in the used part marketplace is not an established practice, and uncertainty remains in how credit is applied to the first use of a material.[122] This gap in data and analysis method is related to end-of-life allocation issues discussed in Principle 6.

Principle 6: Design for Maximum Material Recovery. *Select lightweight materials that are recoverable through existing and planned end-of-life infrastructure and do not impede recoverability of other materials. Seek to use materials that have the maximum potential to reduce demand for primary materials upon recovery and minimize downcycling.*

Lightweight materials often have a complicated end-of-life phase, with issues including incomplete recovery, separation challenges, contamination, and lack of a closed-loop recycling path. For example, in magnesium die-casting operations, typically 50% of the initial material ends up in the part, with a portion of the scrap (dross, chips, and slurry) being too impure for remelting.[123] At vehicle end-of-life, magnesium remains in the nonferrous mix of metals and is often too impure to be recycled.[123] Recycling of cast and wrought aluminum parts generally yields a mix of alloys that are currently only suitable for lower-performance castings, so primary aluminum is needed for all wrought and sheet applications.[90] The use of LW materials in conjunction with more traditional ones in vehicles has also introduced joining and separation issues. For instance, overcasting (or overmolding for composites), in which two materials are brought into contact to form a reaction zone that creates a continuous bond between the two,[124] has enabled the use of mixed material construction to reduce the mass of automotive subsystems such as engine cradles and instrument panel beams.[125] Overcasting/molding can present issues at end-of-life, because separating the two materials is not always technically or economically feasible. Adhesive bonding is an alternative method of joining dissimilar materials (i.e., LW metals, composites, and polymers) that reduces corrosion issues and improves impact resistance,[126] in addition to increasing BIW torsional rigidity, which improves vehicle performance.[127] Disassembly of composites and polymers from metals at end-of-life has been labor-intensive and expensive, but innovative disassembly techniques such as thermally or electrically reversible adhesives or functional additives are potential solutions.[126,128]

Principle 6 asserts that stakeholders should strive to select LW materials that limit these end-of-life challenges as much as possible. Current solutions include designing for manufacturability, recyclability, and durability, which emphasize reducing number of parts, ease of disassembly, and increasing durability.[129] Using fewer materials and reducing part count can also be effective,[130] as demonstrated by the Multi Material Lightweight Vehicle (MMLV), developed by Magna International and Ford Motor Company, which achieved a 23.5% mass reduction using part consolidation and aluminum substitution.[131] Less labor-intensive dismantling can be achieved through modifications to standard designs, and several significant policies have promoted the idea of designing for dismantling and reuse, including the European Parliament's Directive 2000/53/EC, which raised the required reuse of vehicle materials to 85%.[129,132] Development of new aluminum alloys that better match metal streams and do not require additional processing would help to address some of the current limitations with aluminum end-of-life.[91]

Improvements in recovery processes and the ensuing improvements in recovered material quality will affect markets for these materials. Ready availability of high-quality and lower-cost secondary material could stimulate competition with primary material and result in an overall increase in demand for material.

Metrics, Tools, and Gaps in Practice. Metrics used to assess progress on Principle 6 include % recyclability and % recoverability. Other possible metrics include: the recyclability benefit rate (RBR), a ratio of environmental benefits to the environmental burdens;[133] the RBR with an added quality factor, assessed through material properties or economic parameters;[114,133] the circular economy performance indicator (CPI), a ratio of the actual waste treatment option's over the ideal's environmental benefit;[133] remanufacturability;[121] and resource longevity indicators, which measure the contribution

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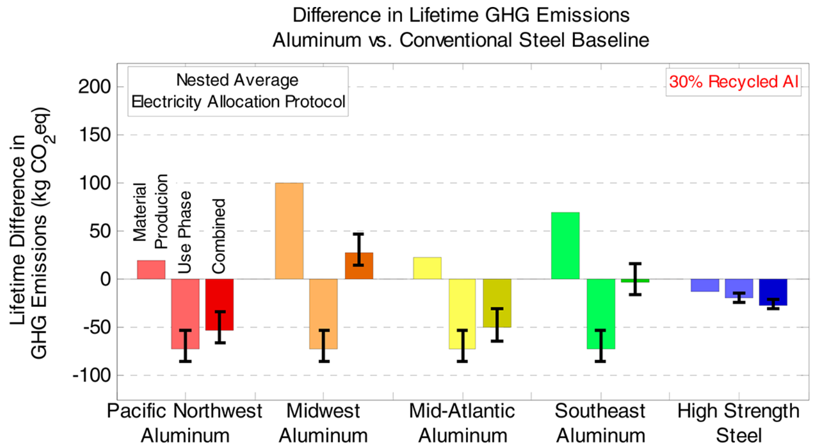

Figure 4. Material production and use-phase impacts for aluminum production in various regions of the United States.[156]

to material retention.[134] Many of these environmental indicators have been developed and used in academic settings to assess material reuse, but few of them are operationalized or used regularly in most industry sectors. This is a gap in end-of-life materials management. Recycling metrics have been used extensively in both the electronics and automotive industries, including disassembly time per product, % recycled material per product, and % recycled or diverted from landfill.[135−138]

Through the use of LCA, OEMs and supply chain component designers can assess the life cycle benefits of LW materials and weigh them against end-of-life burdens (energy consumed separating LW material from other materials[91]). Policies and regulations that advance designing for recoverability as well as research in LW materials recycling should be promoted.

Key barriers to better LW material recovery include a lack of cost-effective technologies to separate and sort materials, which leads to a greater reliance on human labor in many emerging economies such as India and China, and the lack of markets for many recovered materials.[137,139,140] Reclamation of automobile shredder residue (ASR) requires identification of "sortation and reprocessing technologies, life cycle analysis tools, new materials, and coatings removal technologies".[141] The Department of Energy (DoE) has recognized that as lightweight and electric vehicles become more prevalent, recycling will become more challenging. The DoE initiated research into the effects of recycling regulations and reviewed state-of-the-art recycling technologies, in addition to developing and testing new recycling technologies.[137,139] The DoE also facilitated a 2008 workshop among automotive companies, metals suppliers and recyclers, national laboratories, and academia to identify R&D needs for improving future vehicle recycling, which established future priorities.[137] These included developing technologies to remove detrimental impurities, creating more recycling-compatible aluminum alloys, and establishing a cost-effective recycling technology for ASR.

Other gaps include the lack of closed-loop recycling infrastructure for many LW materials such as composites[142] and plastics,[143] operational metrics for assessing end-of-life recovery, and a standardized end-of-life allocation method for LCA work.[61] End-of-life allocation methods tend to either account for burdens when they occur (the recycled content (RC) or cutoff approach) or to assume that recovered materials will offset primary material production and are credited with that offset (the end-of-life recycling (EoLR) or avoided burden approach).[144,145] The RC approach is the more conservative approach, as it captures burdens when they occur in the material life cycle and does not assume recovered material will displace primary material production in the future. Life cycle energy and emissions benefits can vary significantly depending on which approach is used, and the metals industry has advocated for the EoLR approach, as it incentivizes recycling[61,146] and can result in lower burdens because of the EoL credit.[147] There are many misconceptions around the complex task of evaluating and modeling material end-of-life,[148] and a standardized method would add clarity and simplify quantifying progress on this principle.[149] There is also a significant need for research clarifying the economic link between recovered material and primary material, specifically connecting displacement of primary production with recovery of material at end-of-life[150] as well as the degree to which recovered material can displace primary material.[151]

Principle 7: Evaluate Trade-Offs between Life Cycle Phases. *To ensure reduction in overall life cycle impacts, use LCA to quantify changes across life cycle phases and between impact categories because of lightweighting.*

In many instances, trade-offs between life cycle phases or metrics will occur when implementing an LW component or design. These trade-offs need to be carefully evaluated so that the option with the lowest environmental impact is selected. Life cycle impact categories that might be of interest or concern (other than energy and GHGs) include resource depletion, ozone depletion, smog formation, and acidification,[152] though availability and quality of data related to these impact categories is often an issue. Although weighting and normalization techniques exist to select the "optimum" solution when comparing multiple impact categories, their use is controversial, and they are listed as optional techniques by ISO because of the subjectivity inherent in weighting and normalization.[153]

When comparing conventional and LW materials to produce a part, designers need information to compute net life cycle impacts (e.g., energy or GHG emissions) associated with the weight reduction to determine whether use-phase fuel savings outweigh any increase in production burdens.[22] Data required include original and LW part masses, mass dependence of vehicle fuel consumption both with and without powertrain adaptation (as measured by fuel reduction value—FRV), life cycle impacts of processing original and LW materials and part manufacturing, anticipated changes in part lifetime, difference

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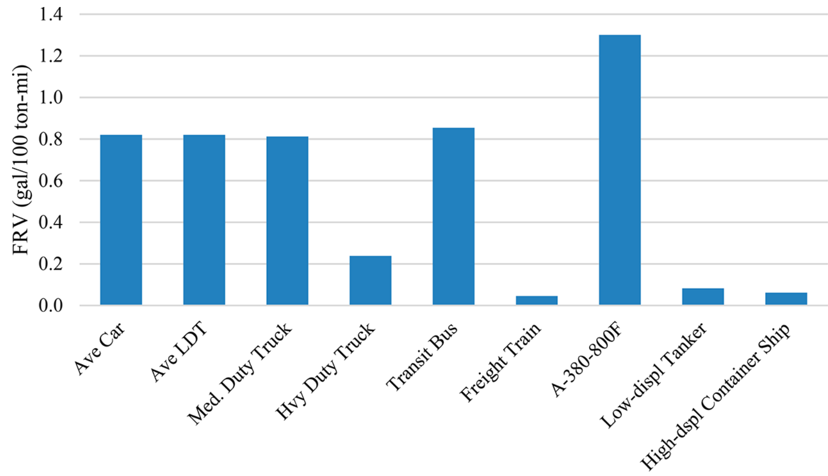

Figure 5. FRVs for transportation vehicles.[15]

in maintenance and repair schedules, and end-of-life treatment employed (EoLR vs RC). The MMLV study discussed in Principle 6 compared life cycle total primary energy (TPE) and global warming potential (GWP) for the 2013 Ford Fusion and MMLV, finding that the lightweight vehicle achieved 16% less TPE and GWP despite an increase in production burdens.[154] The net result over all life cycle phases can typically be approximated by the sum of differences in the material production, manufacturing, and use phases of the life cycle. For example, a study evaluating three air intake manifolds determined that the end-of-life burdens contributed very little, whereas the use phase accounted for at least 60% of life cycle energy.[155]

Trade-offs between life cycle phases are influenced by differences in regional fuel mixes. Figure 4 compares material production and use GHG emissions for aluminum and high-strength steel in different regions of the U.S.[156] In the Midwest region, where coal is still a significant fuel for electricity production, aluminum actually has increased lifetime GHG emissions, which would not have been apparent without a life cycle approach. Variability in life cycle impacts as a result of geography is also apparent at the global scale.[82]

Metrics, Tools, and Gaps in Practice. LCI tools such as GREET, SimaPro, and GaBi are used to assess life cycle trade-offs. These tools list important metrics such as life cycle energy and GHG emissions as well as other life cycle indicators. Note that life cycle databases can be incomplete, outdated, or regionally specific. Data on every step in material and part production should ideally be available but typically are not. Generally, the material production and use phases of the vehicle life cycle are dominant and can be used as a reasonable approximation in assessing trade-offs. Trade-offs in cost, performance, and environmental aspects should all be considered, as discussed in Principle 1, and cost/benefit analyses can be used to evaluate these trade-offs.

Principle 8: Develop Lightweighting Applications To Maximize Benefits. *Decision-makers seeking to improve environmental performance across the transportation sector should prioritize lightweighting applications that achieve the greatest environmental benefit. Powertrain, mode, fleet distribution of vehicle types and use-phase energy mix in the deployment market all influence environmental benefit.*

The net benefit of lightweighting will differ based on a variety of factors that influence vehicle fuel consumption (and associated emissions), including powertrain, vehicle mode and duty cycle, the types of vehicles within the operational fleet, and the kind of fuel being used for vehicle operation. The magnitude of savings from lightweighting depends on the vehicle's powertrain type. Studies of life cycle GHG emissions of conventional and LW versions of an internal combustion engine vehicle (ICEV), a hybrid electric vehicle (HEV), and a battery electric vehicle (BEV) found that the more efficient electrified powertrains (HEV and BEV) result in smaller fuel savings and GHG reductions from lightweighting than ICEVs.[157,158]

FRV measures the change in fuel consumption for a reduction in mass and is a function of vehicle type and duty cycle.[9,10,22,159] Higher FRV implies a larger reduction in fuel consumption for a given change in vehicle mass. Figure 5 indicates a variety of modal FRVs.[15] Class 8 trucks are more fuel-intensive (i.e., use more fuel to move a kg of cargo a given distance) than rail and ships,[160−163] suggesting that trucks should be prioritized for lightweighting. For freight modes, the mass reduced from the vehicle may be added back on as cargo if the vehicle's mass capacity has not been reached. Life cycle inventory tools can be utilized to understand the implications of lightweighting different modes based on available information, such as modal FRV, how much mass can be reduced from the vehicle, and whether that reduced mass will be replaced with cargo.[160,11] Because different modes vary in fleet size and vehicle lifetime, it is important for OEMs to consider fleetwide lightweighting effects.[164,165] Even though energy savings from lightweighting a single car are small relative to larger vehicles such as airplanes and ferries, they could collectively realize the greatest total energy savings because of the size of the automobile fleet.[11]

Fuel type influences the life cycle impact of lightweighting. A comparison of total fuel cycle burdens of petroleum, biofuel, and natural gas fuels for heavy-duty trucks determined that biodiesel and compressed natural gas result in fewer emissions.[166] Modes and regions that use dirtier fuels (i.e., more emissions per unit of energy consumed) will experience a greater reduction in emissions than those that use cleaner fuels, and so, lightweighting will result in the greatest reduction in dirtier regions. Relying on electricity will generally reduce emissions from vehicle operation,[167−170] though the fuel mix (and emissions) for electricity generation varies regionally and nationally.[171,172] It is possible, if unlikely, that this regional

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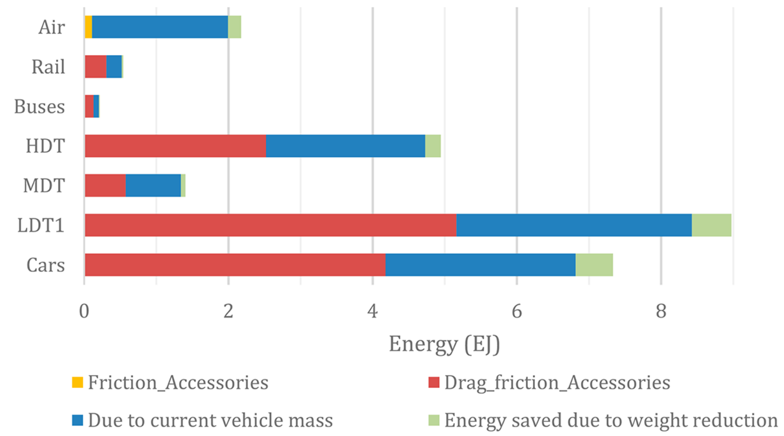

Figure 6. Energy use by mode upon 20% reduction of vehicle mass (based on FRVs from ref 15).

variability could result in higher emissions for EVs than for ICEVs.[173,174] FRV, fleet size, fleet turnover, and fuel type all need to be considered to ensure the most effective lightweighting strategy is deployed.

Metrics, Tools, and Gaps in Practice. Metrics that can be used to assess progress toward maximum lightweighting benefits include life cycle indicators (energy, GHG emissions, etc.) and FRV. Another physics-based approach to assessing the effect of mass reduction on fuel consumption is mass-induced fuel consumption (MIF).[13] MIF allocates total vehicle fuel consumption to mass by calculating mass-related energy use over total energy use.[13,175] Useful tools include ANL's GREET Fleet Footprint Calculator, which estimates the petroleum consumed and greenhouse gases emitted by fleets of medium- and heavy-duty vehicles.[176] Although calculators for other modes are not currently available, GREET can be used to estimate fleet wide impacts by scaling up available individual vehicle values.[29] ANL's AFLEET Tool, based on GREET data, allows a determination of the environmental costs and benefits of alternative fuel at the fleet scale,[177] and the GREET VISION Model[178] incorporates market penetration of advanced vehicles and alternative fuels. ANL's POLARIS tool models large-scale transportation systems and can reflect lightweighting benefits at a fleetwide scale.[179] Fleet size data by mode are not always available, which is a gap in assessing progress on Principle 8. Regional and national GHG reduction policy would likely promote lightweighting.[160] Fuel economy regulations, such as CAFE standards in the U.S., do promote lightweighting[180,181] but focus primarily on the use phase.

Principle 9: Identify Broader System Opportunities. *Evaluate additional benefits resulting from component and vehicle lightweighting, including secondary mass savings and resized and alternative powertrains. Identify and characterize system-level benefits and costs of lighter vehicles (e.g., transportation infrastructure, vehicle miles traveled (VMT) rebound effect) to provide guidance toward enhanced environmental sustainability.*

Vehicle lightweighting can result in additional benefits, such as secondary mass savings (SMS) and powertrain adaptation and resizing.[20,182−185] The size and mass of some vehicle components are driven by the mass of others,[182] so lightweighting one component can result in lightweighting of other components. The total mass reduction in these other components is known as secondary mass savings. Depending on when mass savings are identified and the flexibility in altering vehicle design, it may be possible to achieve more than a kg of SMS per kg of primary mass reduction,[184,186] though there is a lack of agreement in the literature related to the potential of SMS.[187] Powertrain adaptation is another technique employed in conjunction with vehicle lightweighting. Taking mass off a vehicle alters the vehicle's performance, and powertrains are often adjusted to restore the vehicle to original performance, resulting in improved fuel efficiency.[22,61,175,188] Although powertrain adaptation is promising for additional mass reduction and is recognized as significant in life cycle assessments of lightweighting,[61] guidelines for it do not currently exist. A manufacturer may decide to reduce the mass of a vehicle, but if powertrains are designed without considering lightweighting decisions for the full range of vehicles that will use them, then the potential benefits of SMS will not be realized.

VMT rebound is also a potential consequence of vehicle lightweighting. Increased fuel efficiency enables an increase in vehicle miles driven because of reduced fuel cost per mile. It is also important to identify the potential consequences of lightweighting at the transportation system level. There is a direct relationship between vehicle weight, pavement design (thickness and construction and maintenance cost), and road damage.[189] Lightweighting vehicles could reduce damage to roads but only if the reduced mass is not added back as additional cargo, resulting in the same gross vehicle weight.

Another potential consequence of widespread adoption of lightweighting is a shift in demand for (and cost of) materials. For materials with many nonvehicular uses (e.g., steel and aluminum), these shifts may not be catastrophic for producers, but the threats and opportunities presented by such a shift could be large for manufacturers of materials without many other uses. These are not strictly environmental issues, but environmental effects could be assessed with a consequential life cycle analysis, which is intended to evaluate systemic changes like large-scale shifts in material flows and VMT rebound mentioned above.

Metrics, Tools, and Gaps in Practice. Total vehicle mass reduction, as well as fuel economy improvements both with and without powertrain adaptation, can be used to understand the overall effects of lightweighting measures.[182] Gaps include challenges in isolating and quantifying the effects of SMS and powertrain adaptation on infrastructure and rebound effects. Quantified and credible fuel consumption reductions resulting from lightweighting can inform policy-makers concerned with these two effects on environmental and cost drivers. There is a need to identify and understand the life cycle consequences of

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vehicle mass on road infrastructure and maintenance and repair to fully quantify lightweighting benefits.[190]

Principle 10: Develop and Implement Policies To Advance Life Cycle Environmental Performance. *Implement holistic policies that support the adoption of materials, technologies, and strategies that lead to better environmental outcomes and avoid shifting burden across life cycle phases.*

Legislation has been recognized as a useful strategy to influence the behavior of industry.[96,191] Rebitzer et al.[192] have advocated LCA in policy-making, though this would require manufacturers to provide reliable certification data for compliance. The U.S. EPA light-duty GHG regulation is an example of policy to improve use-phase environmental performance, though it does not account for other life cycle phases. European vehicle recycling targets, although focused on end-of-life, will require design, material, and recycling technology changes.[193]

Adopting a life cycle approach helps stakeholders across the entire life cycle be better environmental stewards. Legislation and funding can influence the technologies that are researched, developed, and deployed. Policy is an important tool in steering attention to modes and strategies that have the greatest aggregate impact on improving environmental performance.

Figure 6 plots total energy consumed by transportation mode in the U.S. in 2015 and shows that light-duty vehicles (i.e., cars and light-duty trucks) present the greatest opportunity for systemwide fuel consumption reduction because of the large number of these vehicles. The overall potential for energy savings resulting from vehicle lightweighting is significant, given that roughly half the energy spent in wheeled transportation vehicles and the majority of energy used in aircraft is used to move vehicle mass[15] and that 28 quads (29.5 EJ) were used for U.S. transportation in 2016.[194] A 20% reduction in vehicle mass is estimated to reduce U.S. fleet fuel consumption in cars by 0.52 EJ, light-duty trucks by 0.55 EJ, medium- and heavy-duty trucks by 0.28 EJ, airplanes by 0.18 EJ, and buses and rail by 0.03 EJ—totaling 1.56 EJ, approximately a 5% use-phase energy savings.[15]

To capture this opportunity, policy focused on light-weighting cars and light-duty trucks (beyond CAFE) could be prioritized and expanded. Internal industry policies can also be effective. There have been individual as well as joint initiatives among industry stakeholders to adopt LCA to guide decision-making,[138,188,195,196] including those highlighting the benefits of an LW aluminum pick-up truck.[197]

Metrics, Tools, and Gaps in Practice. It is a significant challenge to measure policy effectiveness directly. Metrics that can be used to assess progress on Principle 10 include the number of life cycle policies currently implemented and metrics that measure improvement in life cycle indicators over time (e.g., fleet fuel economy, mass fraction of vehicle recovered at end-of-life, amount of primary material production avoided, energy intensity of materials used). Tools that can be used to characterize impacts at the fleet scale include the GREET VISION model and Autonomie's POLARIS. Although there has been a recognition by industry and the EPA that burdens from production and end-of-life phases will likely make up a more significant share of total burdens as use-phase regulations become more stringent,[198] there are currently no policies addressing this issue. Other gaps include lack of modal life cycle data, policies that address life cycle burdens and material recovery, and industry adoption of policies.

DISCUSSION

Sets of principles focused on environmental performance (i.e., green principles[39,46,47]) vary in their generality, and some sets include both general and specific principles. Green engineering principles[39] are more broadly applicable, and the vehicle lightweighting principles presented here are tailored to this application. Some of the examples and applications presented above are quite general (e.g., the material efficiency of additive manufacturing applies to all parts produced with that technology and not only vehicle parts), and some are more specific to vehicle lightweighting (e.g., the trade-off between reducing use-phase burdens through lightweighting and increasing material production and manufacturing burdens).

Green lightweighting principles synthesize models, metrics, and frameworks used to quantify environmental performance,[61] and they provide guidance for stakeholders (including designers, manufacturers, suppliers, policy-makers, and researchers) to evaluate trade-offs and make decisions. Trade-offs can be resolved best where complete life cycle inventory data exist for lightweight materials, but principles can also provide guidance in early, less well-defined, or more prospective situations when full LCAs are more difficult to conduct reliably. Pursuing each of these principles individually can lead to enhanced environmental performance, but they are intended to be a holistic set and should be used together to evaluate the inevitable trade-offs, between life cycle phases and between impact categories, that arise when pursuing a vehicle lightweighting effort.

Current practice is to prioritize economic and vehicle performance requirements when considering the design, manufacture, deployment, operation, and retirement of vehicle systems, and the manufacturing and use phases dominate decision-making. These green lightweighting principles raise awareness and promote the consideration of broader perspectives by those who are seeking to improve life cycle environmental performance across life cycle phases and across scales from individual parts and materials to the larger transportation system.

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Notes

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Environ. Sci. Technol. 2019, 53, 4063−4077

REFERENCES

(1) Kojima, K.; Ryan, L. *Transport Energy Efficiency*; IEA, 2010.
(2) EPA; NHTSA. 2017 and Later Model Year Light-Duty Vehicle Greenhouse Gas Emissions and Corporate Average Fuel Economy Standards. *Fed. Regist.* **2012**; *77* (199), Book 2.
(3) Ford Motor Company. *Sustainability Report 2016/2017*; 2017.
(4) Cheah, L.; Heywood, J. Meeting U.S. Passenger Vehicle Fuel Economy Standards in 2016 and Beyond. *Energy Policy* **2011**, *39* (1), 454−466.
(5) Taub, A. I. *MRS Bull.* **2006**, *31* (April), 336−343.
(6) Kasseris, E. P.; Heywood, J. B. Comparative Analysis of Automotive Powertrain Choices for the Next 25 Years. *SAE Tech. Pap. Ser.* **2007**, 2007-01-1605.
(7) Cannon, J. S., Sperling, D., Eds. *Reducing Climate Impacts in the Transportation Sector*; Springer: Dordrecht, 2009.
(8) Mackenzie, D.; Heywood, J.; Zoepf, S. Determinants of US Passenger Car Weight. *Int. J. Veh. Des.* **2014**, *65* (1), 73−93.
(9) Kim, H. C.; Wallington, T. J. Life-Cycle Energy and Greenhouse Gas Emission Benefits of Lightweighting in Automobiles: Review and Harmonization. *Environ. Sci. Technol.* **2013**, *47* (12), 6089−6097.
(10) Koffler, C.; Rohde-Brandenburger, K. On the Calculation of Fuel Savings through Lightweight Design in Automotive Life Cycle Assessments. *Int. J. Life Cycle Assess.* **2010**, *15* (1), 128−135.
(11) Helms, H.; Lambrecht, U. L. The Potential Contribution of Light-Weighting to Reduce Transport Energy Consumption. *Int. J. Life Cycle Assess.* **2007**, *Special Issue 12* (1), 58−64.
(12) Sullivan, J. L.; Hu, J. Life Cycle Energy Analysis for Automobiles. *SAE Tech. Pap. Ser.* **1995**, 951829.
(13) Kim, H. C.; Wallington, T. J. Life Cycle Assessment of Vehicle Lightweighting: A Physics-Based Model of Mass-Induced Fuel Consumption. *Environ. Sci. Technol.* **2013**, *47* (24), 14358−14366.
(14) Ross, M. Fuel Efficiency and the Physics of Automobiles. *Contemp. Phys.* **1997**, *38* (6), 381−394.
(15) Sullivan, J. L.; Lewis, G. M.; Keoleian, G. A. Effect of Mass on Multimodal Fuel Consumption in Moving People and Freight in the U.S. *Transp. Res. Part D Transp. Environ.* **2018**, *63*, 786−808.
(16) Sovran, G.; Blaser, D. Quantifying the Potential Impacts of Regenerative Braking on a Vehicle's Tractive-Fuel Consumption for the U. S., European, and Japanese Driving Schedules. *SAE Tech. Pap. Ser.* **2006**, 2006-1-664.
(17) Caffrey, C.; Bolon, K.; Kolwich, G.; Johnston, R.; Shaw, T. Cost-Effectiveness of a Lightweight Design for 2020−2025: An Assessment of a Light-Duty Pickup Truck. *SAE Tech. Pap. Ser.* **2015**, 2015-01-0559.
(18) Kollamthodi, S.; Kay, D.; Skinner, I.; Dun, C.; Hausberger, S. *The Potential for Mass Reduction of Passenger Cars and Light Commercial Vehicles in Relation to Future CO2 Regulatory Requirements*; Report for the European Comission—DG Climate Action; Ref. CLIMA.C.2/FRA/2013/0006/SR1; 2015, No. 3.
(19) Caffrey, C.; Bolon, K.; Harris, H.; Kolwich, G.; Johnston, R.; Shaw, T. Cost-Effectiveness of a Lightweight Design for 2017−2020: An Assessment of a Midsize Crossover Utility Vehicle. *SAE Tech. Pap. Ser.* **2013**, 2013-01-0656.
(20) Lutsey, N. *Review of Technical Literature and Trends Related to Automobile Mass-Reduction Technology*; UCD-ITS-RR-10-10; 2010; pp 1−40.
(21) Vehicle Technologies Office. *Workshop Report: Light-Duty Vehicles Technical Requirements and Gaps for Lightweight and Propulsion Materials*; 2013.
(22) Kelly, J. C.; Sullivan, J. L.; Burnham, A.; Elgowainy, A. Impacts of Vehicle Weight Reduction via Material Substitution on Life-Cycle Greenhouse Gas Emissions. *Environ. Sci. Technol.* **2015**, *49* (20), 12535−12542.
(23) Fras, E.; Gorny, M. Thin Wall Austempered Ductile Iron (TWADI). *Arch. Foundry Eng.* **2009**, *9* (3), 45−48.
(24) Eisuke, N.; Koichi, A.; Tatsuya, F.; Sadato, H. Some Basic Research for Thin-Wall Casting Technology. *J. Mater. Process. Technol.* **1997**, *63* (1−3), 779−783.
(25) Labrecque, C.; Gagné, M. Optimizing the Mechanical Properties of Thin-Wall Ductile Iron Castings. *Trans. Am. Foundry Soc.* **2005**, *113*, 05-116(05).
(26) Labrecque, C.; Gagné, M.; Javaid, A.; Sahoo, M. Production and Properties of Thin-Wall Ductile Iron Castings. *Int. J. Cast Met. Res.* **2003**, *16* (1−3), 313−317.
(27) Jhaveri, K.; Lewis, G. M.; Sullivan, J. L.; Keoleian, G. A. Life Cycle Assessment of Thin-Wall Ductile Cast Iron for Automotive Lightweighting Applications. *Sustain. Mater. Technol.* **2018**, *15*, 1.
(28) U.S. EPA; U.S. DOT; CARB. *Appendix to Draft Technical Assessment Report: Midterm Evaluation of Light-Duty Vehicle Greenhouse Gas Emission Standards and Corporate Average Fuel Economy Standards for Model Years 2022−2025*; EPA-420-D-16-900app; **2016**.
(29) Argonne National Laboratory. GREET Vehicle-Cycle Model - GREET2_2017 version. https://greet.es.anl.gov.
(30) Mayyas, A. T.; Qattawi, A.; Mayyas, A. R.; Omar, M. A. Life Cycle Assessment-Based Selection for a Sustainable Lightweight Body-in-White Design. *Energy* **2012**, *39* (1), 412−425.
(31) Kampe, S. L. Incorporating Green Engineering in Materials Selection and Design. *Proceedings of The 2001 Green Engineering Conference: Sustainable and Environmentally-Conscious Engineering*, Roanoke, VA, July 29−31, 2001.
(32) Allione, C.; De Giorgi, C.; Lerma, B.; Petruccelli, L. From Ecodesign Products Guidelines to Materials Guidelines for a Sustainable Product. Qualitative and Quantitative Multicriteria Environmental Profile of a Material. *Energy* **2012**, *39* (1), 90−99.
(33) Jambor, A.; Beyer, M. New Cars — New Materials. *Mater. Eng.* **1997**, *18*, 203−209.
(34) Kim, J.; Yoon, H.; Lee, S.; Lee, W.; Shin, K. Durability Evaluation of the Composite Bogie Frame Under Different Shapes and Loading Conditions. *Proceedings of the 18th International Conference on Composite Materials.*
(35) SETAC. *A Technical Framework for Life-Cycle Assessment: Workshop Report: August 18−23, 1990, Smuggler's Notch, Vermont*; Fava, J. A., et al., Eds.; Society of Environmental Toxicology and Chemistry: Penascola, FL, 1991.
(36) ISO. *ISO 14040:2006 Environmental Management - Life Cycle Assessment - Principles and Framework*; International Organization for Standardization: Geneva, 2006.
(37) ISO. *ISO 14025:2006 Environmental Labels and Declarations - Type III Environmental Declarations - Principles and Procedures*; International Organization for Standardization: Geneva, 2006.
(38) Anastas, P. T.; Warner, J. C. *Green Chemistry: Theory and Practice*; Oxford University Press, 1998.
(39) Anastas, P. T.; Zimmerman, J. B. Design through the 12 Principles of Green Engineering. *Environ. Sci. Technol.* **2003**, *37* (5), 94A−101A.
(40) Abraham, M. A.; Nguyen, N. Green Engineering: Defining the Principles" - Results from the Sandestin Conference. *Environ. Prog.* **2003**, *22* (4), 233−236.
(41) Hunter, S.; Helling, R.; Shiang, D. Integration of LCA and Life-Cycle Thinking within the Themes of Sustainable Chemistry & Engineering. *Life Cycle Assessment Handbook: A Guide for Environmentally Sustainable Products* **2012**, 369.
(42) Hunter, S. E.; Helling, R. K. A Call for Technology Developers to Apply Life Cycle and Market Perspectives When Assessing the Potential Environmental Impacts of Chemical Technology Projects. *Ind. Eng. Chem. Res.* **2015**, *54* (16), 4003−4010.
(43) Helling, R. Driving Innovation through Life-Cycle Thinking. *Clean Technol. Environ. Policy* **2015**, *17* (7), 1769−1779.
(44) Shonnard, D. R.; Kicherer, A.; Saling, P. Industrial Applications Using BASF Eco-Efficiency Analysis: Perspectives on Green Engineering Principles. *Environ. Sci. Technol.* **2003**, *37* (23), 5340−5348.
(45) Saling, P.; Kicherer, A.; Dittrich-Krämer, B.; Wittlinger, R.; Zombik, W.; Schmidt, I.; Schrott, W.; Schmidt, S. Eco-Efficiency Analysis by BASF: The Method. *Int. J. Life Cycle Assess.* **2002**, *7*, 203.
(46) McDonough, W.. *The Hannover Principles: Design for Sustainability*; Prepared for EXPO 2000 The World's Fair, Hannover, Germany, 1992.

DOI: 10.1021/acs.est.8b05897
Environ. Sci. Technol. 2019, 53, 4063−4077

(47) Arbabzadeh, M.; Johnson, J. X.; Keoleian, G. A.; Rasmussen, P. G.; Thompson, L. T. Twelve Principles for Green Energy Storage in Grid Applications. *Environ. Sci. Technol.* **2016**, *50* (2), 1046−1055.
(48) Arenas, L. F.; Ponce de León, C.; Walsh, F. C. Engineering Aspects of the Design, Construction and Performance of Modular Redox Flow Batteries for Energy Storage. *J. Energy Storage* **2017**, *11*, 119−153.
(49) Richa, K.; Babbitt, C. W.; Gaustad, G. Eco-Efficiency Analysis of a Lithium-Ion Battery Waste Hierarchy Inspired by Circular Economy. *J. Ind. Ecol.* **2017**, *21* (3), 715−730.
(50) Giudice, F.; La Rosa, G.; Risitano, A. Materials Selection in the Life-Cycle Design Process: A Method to Integrate Mechanical and Environmental Performances in Optimal Choice. *Mater. Eng.* **2005**, *26* (1), 9−20.
(51) Kaspar, J.; Vielhaber, M. Sustainable Lightweight Design - Relevance and Impact on the Product Development & Lifecycle Process. *Procedia Manuf.* **2017**, *8* (October), 409−416. 2016
(52) Luk, J. M.; Kim, H. C.; De Kleine, R.; Wallington, T. J.; MacLean, H. L. Review of the Fuel Saving, Life Cycle GHG Emission, and Ownership Cost Impacts of Lightweighting Vehicles with Different Powertrains. *Environ. Sci. Technol.* **2017**, *51* (15), 8215−8228.
(53) Cole, G. S. Issues That Influence Magnesium's Use in the Automotive Industry. *Mater. Sci. Forum* **2003**, *419−422*, 43−50.
(54) Aghion, E.; Bronfin, B. Magnesium Alloys Development towards the 21st Century. *Mater. Sci. Forum* **2000**, *350−351*, 19−30.
(55) Song, G.-L. Corrosion Behavior and Prevention Strategies for Magnesium (Mg) Alloys. *Corrosion prevention of magnesium alloys* **2013**, 3−37.
(56) Kleiner, M.; Geiger, M.; Klaus, A. Manufacturing of Lightweight Components by Metal Forming. *CIRP Ann.* **2003**, *52* (2), 521−542.
(57) Beyene, A. T.; Koricho, E. G.; Belingardi, G.; Martorana, B. Design and Manufacturing Issues in the Development of Lightweight Solution for a Vehicle Frontal Bumper. *Procedia Eng.* **2014**, *88*, 77−84.
(58) Sun, Z. Joining Dissimilar Material Combinations: Materials and Processes. *Int. J. Mater. Prod. Technol.* **1995**, *10* (1−2), 16−26.
(59) Ashby, M. F. Multi-Objective Optimization in Material Design and Selection. *Acta Mater.* **2000**, *48* (1), 359−369.
(60) Ashby, M., *Material and Process Selection Charts*; 2010, http://www.grantadesign.com/download/pdf/teaching_resource_books/2-Materials-Charts-2010.pdf
(61) Hottle, T.; Caffrey, C.; McDonald, J.; Dodder, R. Critical Factors Affecting Life Cycle Assessments of Material Choice for Vehicle Mass Reduction. *Transp. Res. Part D Transp. Environ.* **2017**, *56* (August), 241−257.
(62) Sverdrup, H. U.; Ragnarsdottir, K. V.; Koca, D. Aluminium for the Future: Modelling the Global Production, Market Supply, Demand, Price and Long Term Development of the Global Reserves. *Resour. Conserv. Recycl.* **2015**, *103*, 139−154.
(63) Zhang, Z.; Jiang, G.; Wang, X.; Zhang, J. Development and Utilization of the World's and China's Bulk Mineral Resources and Their Supply and Demand Situation in the Next Twenty Years. *Acta Geol. Sin.* **2016**, *90* (4), 1370−1417.
(64) Peters, J. F.; Weil, M. A Critical Assessment of the Resource Depletion Potential of Current and Future Lithium-Ion Batteries. *Resources* **2016**, *5* (46), 46.
(65) Alonso, E.; Gregory, J.; Field, F.; Kirchain, R. Material Availability and the Supply Chain: Risks, Effects, and Responses. *Environ. Sci. Technol.* **2007**, *41* (19), 6649−6656.
(66) Legers, L. *The Trouble with Lithium 2: Under the Microscope*; Meridian International Research, 2008; pp 1−54.
(67) Tahil, W. *The Trouble with Lithium: Implications of Future PHEV Production for Lithium Demand*; Meridian International Research, 2006; pp 1−14.
(68) Larcher, D.; Tarascon, J. M. Towards Greener and More Sustainable Batteries for Electrical Energy Storage. *Nat. Chem.* **2015**, *7* (1), 19−29.
(69) Scrosati, B.; Hassoun, J.; Sun, Y.-K. Lithium-Ion Batteries. A Look into the Future. *Energy Environ. Sci.* **2011**, *4* (9), 3287.
(70) Gaines, L., Nelson, P., Lithium Ion Batteries: Possible Materials Issues. In *13th Battery Materials Recycling Seminar and Exhibit*, Fort Lauderdale FL, March 17, 2009.
(71) U.S. Geological Survey. *Mineral Commodity Summaries - Magnesium Metal*; 2018.
(72) Urbance, R. J.; Field, F.; Kirchain, R.; Roth, R.; Clark, J. P. Market Model Simulation: The Impact of Increased Automotive Interest in Magnesium. *JOM* **2002**, *54* (8), 25−33.
(73) Alonso, E.; Sherman, A. M.; Wallington, T. J.; Everson, M. P.; Field, F. R.; Roth, R.; Kirchain, R. E. Evaluating Rare Earth Element Availability: A Case with Revolutionary Demand from Clean Technologies. *Environ. Sci. Technol.* **2012**, *46* (6), 3406−3414.
(74) Allwood, J. M.; Ashby, M. F.; Gutowski, T. G.; Worrell, E. Material Efficiency: A White Paper. *Resour. Conserv. Recycl.* **2011**, *55* (3), 362−381.
(75) Sverdrup, H. U.; Ragnarsdottir, K. V.; Koca, D. An Assessment of Metal Supply Sustainability as an Input to Policy: Security of Supply Extraction Rates, Stocks-in-Use, Recycling, and Risk of Scarcity. *J. Cleaner Prod.* **2017**, *140*, 359−372.
(76) Clift, R.; Wright, L. Relationships between Environmental Impacts and Added Value along the Supply Chain. *Technol. Forecast. Soc. Change* **2000**, *65* (3), 281−295.
(77) Fitch, P. E.; Smith Cooper, J. Life Cycle Energy Analysis as a Method for Material Selection. *J. Mech. Des.* **2004**, *126* (5), 798.
(78) Halada, K.; Ijima, K.; Yagi, K. Database for MLCA (Materials Environmental Life Cycle Analysis). *ASTM Spec. Technol. Publ.* **1997**, *1311*, 171−188.
(79) Azapagic, A. Developing a Framework for Sustainable Development Indicators for the Mining and Minerals Industry. *J. Cleaner Prod.* **2004**, *12* (6), 639−662.
(80) EIA. Energy Use in Industry - Energy Explained, Your Guide To Understanding Energy. https://www.eia.gov/energyexplained/index.php?page=us_energy_industry (accessed July 19, 2018).
(81) Colett, J. S.; Kelly, J. C.; Keoleian, G. A. Using Nested Average Electricity Allocation Protocols to Characterize Electrical Grids in Life Cycle Assessment. *J. Ind. Ecol.* **2016**, *20* (1), 29−41.
(82) McMillan, C. A.; Keoleian, G. A. Not All Primary Aluminium Is Created Equal: Life Cycle Greenhouse Gas Emissions from 1990 to 2005. *Environ. Sci. Technol.* **2009**, *43* (5), 1571−1577.
(83) Benavides, P. T.; Dai, Q.; Sullivan, J. L.; Kelly, J. C.; Dunn, J. B. Material and Energy Flows Associated with Select Metals in GREET 2. Molybdenum, Platinum, Zinc, Nickel, Silicon. *OSTI.GOV* **2015**, ANL/ESD−15/11.
(84) Cui, J.; Roven, H. J. Recycling of Automotive Aluminum. *Trans. Nonferrous Met. Soc. China* **2010**, *20* (11), 2057−2063.
(85) Amini, S. H.; Remmerswaal, J. A. M.; Castro, M. B.; Reuter, M. A. Quantifying the Quality Loss and Resource Efficiency of Recycling by Means of Exergy Analysis. *J. Cleaner Prod.* **2007**, *15* (10), 907−913.
(86) McMillan, C. A.; Skerlos, S. J.; Keoleian, G. A. Evaluation of the Metals Industry's Position on Recycling and Its Implications for Environmental Emissions. *J. Ind. Ecol.* **2012**, *16* (3), 324−333.
(87) Hanko, G.; Antrekowitsch, H.; Ebner, P. Recycling Automotive Magnesium Scrap. *JOM* **2002**, *54* (2), 51−54.
(88) Coulter, S.; Bras, B.; Winslow, G.; Yester, S. Designing for Material Separation: Lessons From Automotive Recycling. *J. Mechanical Design* **1998**, *120*, 501−509.
(89) Paraskevas, D.; Kellens, K.; Dewulf, W.; Duflou, J. R. Environmental Modelling of Aluminium Recycling: A Life Cycle Assessment Tool for Sustainable Metal Management. *J. Cleaner Prod.* **2015**, *105*, 357−370.
(90) Nakajima, K.; Takeda, O.; Miki, T.; Matsubae, K.; Nakamura, S.; Nagasaka, T. Thermodynamic Analysis of Contamination by Alloying Elements in Aluminum Recycling. *Environ. Sci. Technol.* **2010**, *44* (14), 5594−5600.

DOI: 10.1021/acs.est.8b05897
Environ. Sci. Technol. 2019, 53, 4063−4077

(91) Das, S. Recycling and Life Cycle Issues for Lightweight Vehicles. *Materials, Design and Manufacturing for Lightweight Vehicles* **2010**, 309.
(92) Probst, L.; Frideres, L.; Cambier, B.; Hommel, S.; PwC Luxembourg. *Sustainable Supply of Raw Materials*; Case Study 59; 2016.
(93) Demaria, F. Shipbreaking at Alang-Sosiya (India): An Ecological Distribution Conflict. *Ecol. Econ.* **2010**, *70* (2), 250−260.
(94) Asmatulu, E.; Overcash, M.; Twomey, J. Recycling of Aircraft: State of the Art in 2011. *J. Ind. Eng.* **2013**, *2013*, 1−8.
(95) Kokubu, K.; Kitada, H. Material Flow Cost Accounting and Existing Management Perspectives. *J. Cleaner Prod.* **2015**, *108*, 1279−1288.
(96) Bey, N.; Hauschild, M. Z.; McAloone, T. C. Drivers and Barriers for Implementation of Environmental Strategies in Manufacturing Companies. *CIRP Ann.* **2013**, *62* (1), 43−46.
(97) Almeida, C. M. V.; Bonilla, S. H.; Giannetti, B. F.; Huisingh, D. Cleaner Production Initiatives and Challenges for a Sustainable World: An Introduction to This Special Volume. *J. Cleaner Prod.* **2013**, *47*, 1−10.
(98) Fysikopoulos, A.; Anagnostakis, D.; Salonitis, K.; Chryssolouris, G. An Empirical Study of the Energy Consumption in Automotive Assembly. *Procedia CIRP* **2012**, *3* (1), 477−482.
(99) Kim, H.-J.; Keoleian, G. A.; Skerlos, S. J. Economic Assessment of Greenhouse Gas Emissions Reduction by Vehicle Lightweighting Using Aluminum and High-Strength Steel. *J. Ind. Ecol.* **2011**, *15* (1), 64−80.
(100) Huang, R.; Riddle, M.; Graziano, D.; Warren, J.; Das, S.; Nimbalkar, S.; Cresko, J.; Masanet, E. Energy and Emissions Saving Potential of Additive Manufacturing: The Case of Lightweight Aircraft Components. *J. Cleaner Prod.* **2016**, *135*, 1559−1570.
(101) Mellor, S.; Hao, L.; Zhang, D. Additive Manufacturing: A Framework for Implementation. *Int. J. Prod. Econ.* **2014**, *149*, 194−201.
(102) The Economist. Solid print. https://www.economist.com/node/21552892 (accessed June 7, 2018).
(103) Atzeni, E.; Salmi, A. Economics of Additive Manufacturing for End-Usable Metal Parts. *Int. J. Adv. Manuf. Technol.* **2012**, *62* (9−12), 1147−1155.
(104) Azzone, G.; Noci, G. Identifying Effective PMSs for the Deployment of "Green" Manufacturing Strategies. *Int. J. Oper. Prod. Manag.* **1998**, *18* (4), 308−335.
(105) Carruth, M. A.; Allwood, J. M.; Moynihan, M. C. The Technical Potential for Reducing Metal Requirements through Lightweight Product Design. *Resour. Conserv. Recycl.* **2011**, *57*, 48−60.
(106) Lanzerath, H.; Tragsdorf, C. Body Lightweight Design and Scalability with Structural Foam Solutions. *SAE Int. J. Mater. Manuf.* **2013**, *6* (2), 232−241.
(107) Joshi, A. M.; Ezzat, H.; Bucknor, N.; Verbrugge, M. Optimizing Battery Sizing and Vehicle Lightweighting for an Extended Range Electric Vehicle. *SAE Tech. Pap. Ser.* **2011**, 2011-01-1078.
(108) Brecher, A.; Brewer, J.; Summers, S.; Patel, S. Characterizing and Enhancing the Safety of Future Plastic and Composite Intensive Vehicles (PCIVs). *Proceedings of the 21st (ESV) International Technical Conference on the Enhanced Safety of Vehicles*, Stuttgart, Germany, June 2009.
(109) Banhart, J.; Garcia-Moreno, F.; Heim, K.; Seeliger, H.Light-Weighting in Transportation and Defence Using Aluminium Foam Sandwich Structures; *Proceedings of the International Symposium on Light Weighting for Defence, Aerospace and Transportation*, 2017.
(110) Mario, H.; Dietrich, W.; Gfrerrer, A.; Lang, J. *Integrated Computer-Aided Design in Automotive Development: Development Processes, Geometric Fundamentals, Methods of CAD, Knowledge-Based Engineering Data Management*; Springer: Berlin, 2013; https://link.springer.com/book/10.1007%2F978-3-642-11940-8#about.
(111) Birchmeier, J. E.; Smith, K. V. Optimization of a Light Truck Rough Road Durability Procedure Using Fatigue Analysis Methology. *SAE Tech. Pap. Ser.* **1982**, 187−195.
(112) Tivey, C. J. The Utilization of Fatigue Life Prediction Techniques in Support of a Majaor Vehicle Project. *Proc. Instn Mech Engrs* **1986**, *200* (5), s87−s94.
(113) Schäfer, A.; Jacoby, H. D. Vehicle Technology under CO2 Constraint: A General Equilibrium Analysis. *Energy Policy* **2006**, *34* (9), 975−985.
(114) Ardente, F.; Mathieux, F. Integration of Resource Efficiency and Waste Management Criteria in European Product Policies - Second Phase - Report 3; 2012.
(115) Kim, H. C.; Keoleian, G. A.; Grande, D. E.; Bean, J. C. Life Cycle Optimization of Automobile Replacement: Model and Application. *Environ. Sci. Technol.* **2003**, *37* (23), 5407−5413.
(116) Prendi, L.; Henshaw, P.; Tam, E. K. L. Automotive Coatings with Improved Environmental Performance. *Int. J. Environ. Stud.* **2006**, *63* (4), 463−471.
(117) Garcia-Alonso, D.; Serres, N.; Demian, C.; Costil, S.; Langlade, C.; Coddet, C. Pre-/during-/Post-Laser Processes to Enhance the Adhesion and Mechanical Properties of Thermal-Sprayed Coatings with a Reduced Environmental Impact. *J. Therm. Spray Technol.* **2011**, *20* (4), 719−735.
(118) Mubarok, M. Z.; Wahab; Sutarno; Wahyudi, S. Effects of Anodizing Parameters in Tartaric-Sulphuric Acid on Coating Thickness and Corrosion Resistance of Al 2024 T3 Alloy. *J. Miner. Mater. Charact. Eng.* **2015**, *03* (03), 154−163.
(119) Harscoet, E.; Froelich, D. Use of LCA to Evaluate the Environmental Benefits of Substituting Chromic Acid Anodizing (CAA). *J. Cleaner Prod.* **2008**, *16* (12), 1294−1305.
(120) Nicholas, T.; Zuiker, J. R. On the Use of the Goodman Diagram for High Cycle Fatigue Design. *Int. J. Fract.* **1996**, *80* (2-3), 219−235.
(121) Amezquita, T.; Hammond, R.; Salazar, M.; Bras, B. Characterizing the Remanufacturability of Engineering Systems. *Proc. ASME Adv. Des. Autom. Conf.*, Boston, Sept. 17−20, 1995; Vol. *82*, pp. 271−278.
(122) Smith, V. M.; Keoleian, G. A. The Value of Remanufactured Engines: Life-Cycle Environmental and Economic Perspectives. *J. Ind. Ecol.* **2004**, *8* (1−2), 193−221.
(123) Witik, R. A.; Payet, J.; Michaud, V.; Ludwig, C.; Manson, J.-A. E. Assessing the Life Cycle Costs and Environmental Performance of Lightweight Materials in Automobile Applications. *Composites, Part A* **2011**, *42* (11), 1694−1709.
(124) Liu, T.; Wang, Q. D.; Liu, P.; Sun, J. W.; Yin, X. L.; Wang, Q. G. Microstructure and Mechanical Properties of Overcast Aluminum Joints. *Trans. Nonferrous Met. Soc. China* **2015**, *25* (4), 1064−1072.
(125) Luo, A. A.; Sachdev, A. K.; Powell, B. R. Advanced Casting Technologies for Lightweight Automotive Applications. *China Foundry* **2010**, *7* (4), 463−469.
(126) Lu, Y.; Broughton, J.; Winfield, P. A Review of Innovations in Disbonding Techniques for Repair and Recycling of Automotive Vehicles. *Int. J. Adhes. Adhes.* **2014**, *50*, 119−127.
(127) Feraboli, P.; Masini, A. Development of Carbon/Epoxy Structural Components for a High Performance Vehicle. *Composites, Part B* **2004**, *35* (4), 323−330.
(128) Luo, X.; Lauber, K. E.; Mather, P. T. A Thermally Responsive, Rigid, and Reversible Adhesive. *Polymer* **2010**, *51* (5), 1169−1175.
(129) Mayyas, A.; Qattawi, A.; Omar, M.; Shan, D. Design for Sustainability in Automotive Industry: A Comprehensive Review. *Renewable Sustainable Energy Rev.* **2012**, *16* (4), 1845−1862.
(130) McAuley, J. W. Global Sustainability and Key Needs in Future Automotive Design. *Environ. Sci. Technol.* **2003**, *37* (23), 5414−5416.
(131) Conklin, J.; Beals, R.; Brown, Z. BIW Design and CAE. *SAE Tech. Pap. Ser.* **2015**, 2015-01-0408.
(132) Tian, J.; Chen, M. Sustainable Design for Automotive Products: Dismantling and Recycling of End-of-Life Vehicles. *Waste Manage.* **2014**, *34* (2), 458−467.
(133) Huysman, S.; De Schaepmeester, J.; Ragaert, K.; Dewulf, J.; De Meester, S. Performance Indicators for a Circular Economy: A Case Study on Post-Industrial Plastic Waste. *Resour. Conserv. Recycl.* **2017**, *120*, 46−54.

DOI: 10.1021/acs.est.8b05897
Environ. Sci. Technol. 2019, 53, 4063−4077

(134) Franklin-Johnson, E.; Figge, F.; Canning, L. Resource Duration as a Managerial Indicator for Circular Economy Performance. *J. Cleaner Prod.* **2016**, *133*, 589−598.
(135) Atlee, J.; Kirchain, R. Operational Sustainability Metrics Assessing Metric Effectiveness in the Context of Electronics-Recycling Systems. *Environ. Sci. Technol.* **2006**, *40* (14), 4506−4513.
(136) Keoleian, G. A.; Sullivan, J. L. Materials Challenges and Opportunities for Enhancing the Sustainability of Automobiles. *MRS Bull.* **2012**, *37* (04), 365−373.
(137) Jody, B. J.; Daniels, E. J. End-of-Life Vehicle Recycling: The State of the Art of Resource Recovery from Shredder Residue. *OSTI.GOV* **2007**, ANL/ESD/07-8.
(138) Sullivan, J. L.; Williams, R.; Yester, S.; Coba-Flores, E.; Chubbs, S.; Hentges, S.; Pomper, S. Life Cycle Inventory of a Generic U.S. Family Sedan Overview of Results USCAR AMP Project. *SAE Tech. Pap. Ser.* **1998**, 982160.
(139) Daniels, E. J.; Carpenter, J. A.; Duranceau, C.; Fisher, M.; Wheeler, C.; Winslow, G. Sustainable End-of-Life Vehicle Recycling: R&D Collaboration between Industry and the U.S. DOE. *JOM* **2004**, *56* (8), 28−32.
(140) Reck, B. K.; Graedel, T. E. Challenges in Metal Recycling. *Science (Washington, DC, U. S.)* **2012**, *337* (6095), 690−695.
(141) Gutowski, T. G.; Allen, D. T.; Bauer, D. J.; Bras, B.; Piwonka, T. S.; Sheng, P. S.; Sutherland, J. W.; Thurston, D. L.; Wolff, E. E.; Shelton, R. D. et al. Environmentally Benign Manufacturing. International Technology Research Institute, World Technology (WTEC) Division (Loyola College), http://scienceus.org/wtec/docs/ebm.pdf, 2001.
(142) Palmer, J.; Ghita, O. R.; Savage, L.; Evans, K. E. Successful Closed-Loop Recycling of Thermoset Composites. *Composites, Part A* **2009**, *40* (4), 490−498.
(143) Hopewell, J.; Dvorak, R.; Kosior, E. Plastics Recycling: Challenges and Opportunities. *Philos. Trans. R. Soc., B* **2009**, *364* (1526), 2115−2126.
(144) Frischknecht, R. LCI Modelling Approaches Applied on Recycling of Materials in View of Environmental Sustainability, Risk Perception and Eco-Efficiency. *Int. J. Life Cycle Assess.* **2010**, *15* (7), 666−671.
(145) Geyer, R. Parametric Assessment of Climate Change Impacts of Automotive Material Substitution. *Environ. Sci. Technol.* **2008**, *42* (18), 6973−6979.
(146) Johnson, J. X.; McMillan, C. A.; Keoleian, G. A. Evaluation of Life Cycle Assessment Recycling Allocation Methods. *J. Ind. Ecol.* **2013**, *17* (5), 700−711.
(147) Santero, N.; Hendry, J. Harmonization of LCA Methodologies for the Metal and Mining Industry. *Int. J. Life Cycle Assess.* **2016**, *21*, 1543−1553.
(148) Geyer, R.; Kuczenski, B.; Zink, T.; Henderson, A. Common Misconceptions about Recycling. *J. Ind. Ecol.* **2016**, *20* (5), 1010−1017.
(149) Koffler, C.; Finkbeiner, M. Are We Still Keeping It "Real"? Proposing a Revised Paradigm for Recycling Credits in Attributional Life Cycle Assessment. *Int. J. Life Cycle Assess.* **2018**, *23* (1), 181−190.
(150) Vadenbo, C.; Hellweg, S.; Astrup, T. F. Let's Be Clear(Er) about Substitution: A Reporting Framework to Account for Product Displacement in Life Cycle Assessment. *J. Ind. Ecol.* **2017**, *21* (5), 1078−1089.
(151) Palazzo, J.; Geyer, R.; Startz, R.; Steigerwald, D. G. Causal Inference for Quantifying Displaced Primary Production from Recycling. *J. Cleaner Prod.* **2019**, *210*, 1076−1084.
(152) Lee, K.-M.; Inaba, A. *Life Cycle Assessment: Best Practices of International Organization for Standardization (ISO) 14040 Series*; Center for Ecodesign and LCA (CEL), Ajou University: Suwon, Korea, 2004.
(153) Schmidt, W.-P.; Sullivan, J. Weighting in Life Cycle Assessments in a Global Context. *Int. J. Life Cycle Assess.* **2002**, *7* (1), 5−10.
(154) Bushi, L.; Skszek, T.; Wagner, D. Comparative LCA Study of Lightweight Auto Parts of MMLV Mach-I Vehicle as per ISO 14040/44 LCA Standards and CSA Group 2014 LCA Guidance Document for Auto Parts. *Engineering Solutions for Sustainability* **2015**, 193−208.
(155) Keoleian, G. A.; Kar, K. Elucidating Complex Design and Management Tradeoffs through Life Cycle Design: Air Intake Manifold Demonstration Project. *J. Cleaner Prod.* **2003**, *11* (1), 61−77.
(156) Colett, J. S. *Impacts of Geographic Variation on Aluminum Lightweighted Plug-in Hybrid Electric Vehicle Greenhouse Gas Emissions*. M.S. Thesis, University of Michigan, 2013; Report No. CSS13-25.
(157) Luk, J. M.; Kim, H. C.; De Kleine, R.; Wallington, T. J.; MacLean, H. L. Impact of Powertrain Type on Potential Life Cycle Greenhouse Gas Emission Reductions from a Real World Lightweight Glider. *SAE Tech. Pap. Ser.* **2017**, 2017-01-1274.
(158) Luk, J. M.; Kim, H. C.; De Kleine, R.; Wallington, T. J.; MacLean, H. L. Greenhouse Gas Emission Benefits of Vehicle Lightweighting: Monte Carlo Probabilistic Analysis of the Multi Material Lightweight Vehicle Glider. *Transp. Res. Part D Transp. Environ.* **2018**, *62*, 1−10.
(159) Del Pero, F.; Delogu, M.; Pierini, M. The Effect of Lightweighting in Automotive LCA Perspective: Estimation of Mass-Induced Fuel Consumption Reduction for Gasoline Turbocharged Vehicles. *J. Cleaner Prod.* **2017**, *154*, 566−577.
(160) Nahlik, M. J.; Kaehr, A. T.; Chester, M. V.; Horvath, A.; Taptich, M. N. Goods Movement Life Cycle Assessment for Greenhouse Gas Reduction Goals. *J. Ind. Ecol.* **2016**, *20* (2), 317−328.
(161) Horvath, A. Environmental Assessment of Freight Transportation in the U.S. *Int. J. Life Cycle Assess.* **2006**, *11* (4), 229−239.
(162) Winebrake, J. J.; Corbett, J. J.; Falzarano, A.; Hawker, J. S.; Korfmacher, K.; Ketha, S.; Zilora, S. Assessing Energy, Environmental, and Economic Tradeoffs in Intermodal Freight Transportation. *J. Air Waste Manage. Assoc.* **2008**, *58* (8), 1004−1013.
(163) Comer, B.; Corbett, J. J.; Hawker, J. S.; Korfmacher, K.; Lee, E. E.; Prokop, C.; Winebrake, J. J. Marine Vessels as Substitutes for Heavy-Duty Trucks in Great Lakes Freight Transportation. *J. Air Waste Manage. Assoc.* **2010**, *60* (7), 884−890.
(164) Bandivadekar, A.; Cheah, L.; Evans, C.; Groode, T.; Heywood, J.; Kasseris, E.; Kromer, M.; Weiss, M. Reducing the Fuel Use and Greenhouse Gas Emissions of the US Vehicle Fleet. *Energy Policy* **2008**, *36* (7), 2754−2760.
(165) Das, S.; Graziano, D.; Upadhyayula, V. K. K.; Masanet, E.; Riddle, M.; Cresko, J. Vehicle Lightweighting Energy Use Impacts in U.S. Light-Duty Vehicle Fleet. *Sustain. Mater. Technol.* **2016**, *8*, 5−13.
(166) Meyer, P. E.; Green, E. H.; Corbett, J. J.; Mas, C.; Winebrake, J. J. Total Fuel-Cycle Analysis of Heavy-Duty Vehicles Using Biofuels and Natural Gas-Based Alternative Fuels. *J. Air Waste Manage. Assoc.* **2011**, *61* (3), 285−294.
(167) Ou, X.; Yan, X.; Zhang, X.; Liu, Z. Life-Cycle Analysis on Energy Consumption and GHG Emission Intensities of Alternative Vehicle Fuels in China. *Appl. Energy* **2012**, *90* (1), 218−224.
(168) Singh, B.; Ellingsen, L. A. W.; Strømman, A. H. Pathways for GHG Emission Reduction in Norwegian Road Transport Sector: Perspective on Consumption of Passenger Car Transport and Electricity Mix. *Transp. Res. Part D Transp. Environ.* **2015**, *41*, 160−164.
(169) Song, Q.; Wu, Y.; Li, J.; Wang, Z.; Yu, D.; Duan, H. Well-to-Wheel GHG Emissions and Mitigation Potential from Light-Duty Vehicles in Macau. *Int. J. Life Cycle Assess.* **2018**, *23*, 1916.
(170) Sioshansi, R.; Fagiani, R.; Marano, V. Cost and Emissions Impacts of Plug-in Hybrid Vehicles on the Ohio Power System. *Energy Policy* **2010**, *38* (11), 6703−6712.
(171) Orsi, F.; Muratori, M.; Rocco, M.; Colombo, E.; Rizzoni, G. A Multi-Dimensional Well-to-Wheels Analysis of Passenger Vehicles in Different Regions: Primary Energy Consumption, CO2emissions, and Economic Cost. *Appl. Energy* **2016**, *169*, 197−209.
(172) Woo, J. R.; Choi, H.; Ahn, J. Well-to-Wheel Analysis of Greenhouse Gas Emissions for Electric Vehicles Based on Electricity Generation Mix: A Global Perspective. *Transp. Res. Part D Transp. Environ.* **2017**, *51*, 340−350.

DOI: 10.1021/acs.est.8b05897
Environ. Sci. Technol. 2019, 53, 4063−4077

(173) Hawkins, T. R.; Singh, B.; Majeau-Bettez, G.; Strømman, A. H. Comparative Environmental Life Cycle Assessment of Conventional and Electric Vehicles. *J. Ind. Ecol.* **2013**, *17* (1), 53−64.
(174) Archsmith, J.; Kendall, A.; Rapson, D. From Cradle to Junkyard: Assessing the Life Cycle Greenhouse Gas Benefits of Electric Vehicles. *Res. Transp. Econ.* **2015**, *52*, 72−90.
(175) Kim, H. C.; Wallington, T. J.; Sullivan, J. L.; Keoleian, G. A. Life Cycle Assessment of Vehicle Lightweighting: Novel Mathematical Methods to Estimate Use-Phase Fuel Consumption. *Environ. Sci. Technol.* **2015**, *49* (16), 10209−10216.
(176) Argonne National Laboratory. GREET Fleet - Carbon and Petroleum Footprint Calculator. https://greet.es.anl.gov/fleet_footprint_calculator.
(177) Argonne National Laboratory. AFLEET Tool https://greet.es.anl.gov/afleet (accessed March 20, 2018).
(178) Argonne National Laboratory. VISION Model. https://www.anl.gov/es/vision-model.
(179) Argonne National Laboratory. Autonomie - Expertise \POLARIS. https://www.autonomie.net/expertise/POLARIS.html.
(180) Bastani, P.; Heywood, J. B.; Hope, C. *U.S. Cafe Standards: Potential for Meeting Light-duty Vehicle Fuel Economy Targets*; Massachusetts Institute of Technology, 2012.
(181) Tucker, R. Trends in Automotive Lightweighting. *Met. Finish.* **2013**, *111* (2), 23−25.
(182) Alonso, E.; Lee, T. M.; Bjelkengren, C.; Roth, R.; Kirchain, R. E. Evaluating the Potential for Secondary Mass Savings in Vehicle Lightweighting. *Environ. Sci. Technol.* **2012**, *46* (5), 2893−2901.
(183) Koffler, C. Life Cycle Assessment of Automotive Lightweighting through Polymers under US Boundary Conditions. *Int. J. Life Cycle Assess.* **2014**, *19* (3), 538−545.
(184) Verbrugge, M.; Lee, T.; Krajewski, P.; Sachdev, A.; Bjelkengren, C.; Roth, R.; Kirchain, R. Mass Decompounding and Vehicle Lightweighting. *Mater. Sci. Forum* **2009**, *618-619*, 411−418.
(185) Office of Transportation and Air Quality, EPA; National Highway Traffic Safety Administration, Department of Transportation; California Air Resources Board. *Draft Technical Assessment Report: Midterm Evaluation of Light-Duty Vehicle Greenhouse Gas Emission Standards and Corporate Average Fuel Economy Standards for Model Years 2022−2025*; EPA-420-D-16-900; 2016.
(186) Malen, D. E.; Reddy, K.; *Preliminary Vehicle Mass Estimation Using Empirical Subsystem Influence Coefficients*; Auto/Steel Partnership, 2007.
(187) Raugei, M.; Morrey, D.; Hutchinson, A.; Winfield, P. A Coherent Life Cycle Assessment of a Range of Lightweighting Strategies for Compact Vehicles. *J. Cleaner Prod.* **2015**, *108*, 1168−1176.
(188) Kim, H. C.; Wallington, T. J. Life Cycle Assessment of Vehicle Lightweighting: A Physics-Based Model to Estimate Use-Phase Fuel Consumption of Electrified Vehicles. *Environ. Sci. Technol.* **2016**, *50* (20), 11226−11233.
(189) Battelle. Comprehensive Truck Size and Weight (TS&W) Study: Phase 1 - Synthesis; Working Paper 4; 1995.
(190) Wilde, W. J. Assessing the Effects of Heavy Vehicles on Local Roadways; Final Report 2014-32; Minnesota Department of Transportation, 2014.
(191) Williamson, D.; Lynch-Wood, G.; Ramsay, J. Drivers of Environmental Behaviour in Manufacturing SMEs and the Implications for CSR. *J. Bus. Ethics* **2006**, *67* (3), 317−330.
(192) Rebitzer, G.; Ekvall, T.; Frischknecht, R.; Hunkeler, D.; Norris, G.; Rydberg, T.; Schmidt, W.-P. P.; Suh, S.; Weidema, B. P.; Pennington, D. W. Life Cycle Assessment Part 1: Framework, Goal and Scope Definition, Inventory Analysis, and Applications. *Environ. Int.* **2004**, *30* (5), 701−720.
(193) Kanari, N.; Pineau, J.-L.; Shallari, S. End-of-Life Vehicle Recycling in European Union. *JOM* **2003**, *55* (8), 15−19.
(194) EIA. U.S. energy flow, 2017. https://www.eia.gov/totalenergy/data/monthly/pdf/flow/total_energy.pdf (accessed September 21, 2018).
(195) Ridge, L. EUCAR - Automotive LCA Guidelines - Phase 2. *SAE Tech. Pap. Ser.* **1998**, 982185.
(196) Schmidt, W.-P.; Dahlqvist, E.; Finkbeiner, M.; Krinke, S.; Lazzari, S.; Oschmann, D.; Pichon, S.; Thiel, C. Life Cycle Assessment of Lightweight and End-of-Life Scenarios for Generic Compact Class Passenger Vehicles. *Int. J. Life Cycle Assess.* **2004**, *9* (6), 405−416.
(197) De Kleine, R.; Smith, J.; Kim, H. C.; Wallington, T. In *Life cycle energy demand and greenhouse gas savings from pickup truck lightweighting*; ISIE-ISSST 2017: Science in Support of Sustainable and Resilient Communities, 2017, http://programme.exordo.com/isie2017/delegates/presentation/706/.
(198) EPA. 2017 and Later Model Year Light-Duty Vehicle Greenhouse Gas Emissions and Corporate Average Fuel Economy Standards: EPA Response to Comments; EPA-420-R-12-017; http://programme.exordo.com/isie2017/delegates/presentation/706/, 2012.

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