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Environmentally Responsible Lightweight Passenger Vehicle Design and Manufacturing

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Abstract

The mass reduction of passenger vehicles has been a great focus of academic research and federal policy initiatives of the United States with coordinated funding efforts and even a focus of a Manufacturing USA Institute. The potential benefit of these programs can be described as modest from a societal point of view, for example reducing vehicle mass by up to 25% with modest cost implications (under $5 per pound saved) and the ability to implement with existing manufacturing methods. Much more aggressive reductions in greenhouse gas production are necessary and possible, while delivering the same service. This is demonstrated with a higher-level design thinking exercise on an environmentally responsible lightweight vehicle, leading to the following criteria: lightweight, low aerodynamic drag, long-lived (over 30 years and 2 million miles), adaptable, electric, and used in a shared manner on average over 8 h per day. With these specifications, passenger-mile demand may be met with around 1/10 of the current fleet. Such vehicles would likely have significantly different designs and construction than incumbent automobiles. It is likely future automotive production will be more analogous to current aircraft production with higher costs per pound and lower volumes, but with dramatically reduced financial and environmental cost per passenger mile, with less material per vehicle, and far less material required in the national or worldwide fleets. Subsidiary benefits of this vision include far fewer parking lots, greater accessibility to personal transportation, and improved pedestrian safety, while maintaining a vibrant and engaging economy. The systemic changes to the business models and research and development directions (including lightweight design and manufacturing) are discussed, which could bring forth far more sustainable personal transportation.

Keywords Sustainability · Personal transportation · Lighgweighting · Design

Abbreviations

DOE	Department of energy
EV	Electric vehicle
GHG	Greenhouse gas

1 Introduction

Greenhouse gas (GHG) emission is widely acknowledged as one of the most pressing problems facing humanity. Many corporate, government, and research initiatives are motivated by and heralded as making important gains in our sustainability. This is amply demonstrated by numerous corporate mission statements, political ribbon-cuttings at green facilities, and the introduction of most scientific papers that mention sustainability. Meanwhile, humanity is slipping further from the collective goals of the Paris Accords, to keep the rise in mean global temperature well below 2 °C (35.6 °F) above the pre-industrial level. Figure 1 shows one of the benchmark measures of progress, the Mauna Loa atmospheric concentration of carbon dioxide, which at this writing stands near 420 ppm, and the rate of year-by-year increase is at as high a level as it has been in recorded history [1]. This measure came to significant public attention with Senator Al Gore's *Inconvenient Truth* slide shows, movie, and book

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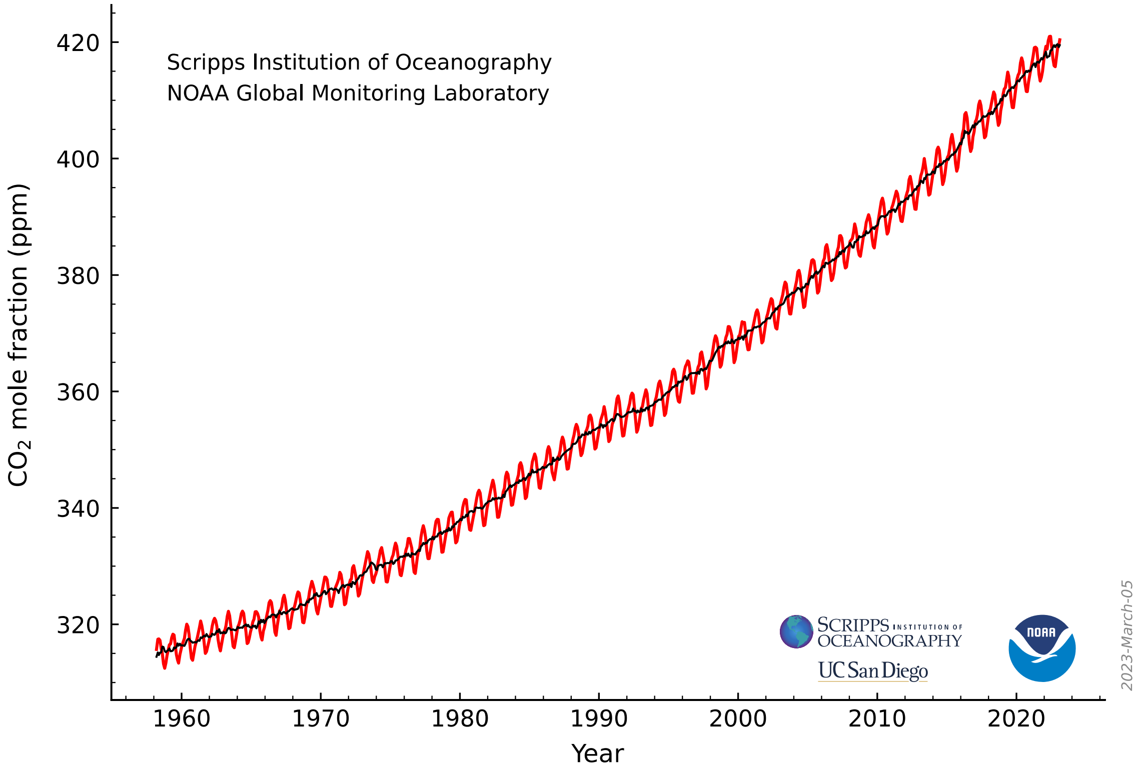

Fig. 1 Atmospheric CO$_2$ observed at Mauna Loa Observatory showing that levels of CO$_2$ are at the highest levels and highest positive rates of change in recorded history [1]

in 2006 [2]. At that time, there were about 380 ppm CO$_2$ and the rate of change has increased substantially. Systemic changes are needed to meet these goals.

Personal vehicle transportation is a significant part of GHG emissions. Emissions arise from both the use of vehicles in the burning of fossil fuels (conventional combustion engine), as well as the production and manufacture of the over 20,000 components, principally steel, aluminum, glass, rubber, copper, and plastics. There is a popular concept that the substitution of electric-powered vehicles for gasoline or fossil-fueled vehicles will eliminate GHG emissions due to personal transportation. However, the energy system is at the early stage of the transition to decarbonized energy sources. The availability of abundant renewable electricity is not yet a reality throughout most of the world. For the US, the Sankey diagrams produced by the US Department of Energy (DOE)'s Lawrence Livermore National Lab [3] provide excellent high-level guidance on energy production and use. The per annum energy flows for 2021 are shown in Fig. 2. The petroleum used in transportation is the largest flow, with one of the lowest rates of conversion to useful energy services, caused by the low efficiency of combustion engines. Considering the shift to electricity, natural gas and nuclear are currently significant sources of electricity generation, while wind and solar only contribute several percent to the total energy supply. The expansion of renewable electricity will require time and infrastructure. While achieving 100% renewable electricity grids is technically possible [4] and following empirical deployment trends, renewables may challenge the dominance of fossil fuels within a decade [5], full electrification of the vehicle fleet in the current paradigm will add excessive demand during the transition. Milovanoff et al. [6] estimated that electrifying light-duty vehicle fleet emissions by 2050 will require more than 350 million on-road EVs and half of the national electricity demand (compared to around 2% today). Electric vehicles also compete with renewable infrastructure for critical raw materials for battery materials, as well as copper, aluminum, and steel [7]. As electric vehicles are typically more materials-intensive, and the production of these materials is currently difficult to decarbonize, the majority of the life-cycle emissions burden shifts from use to production.

Academic papers [6] and popular media[8] have cautioned that the simple replacement of fossil fuel vehicles with electric vehicles may be woefully insufficient to provide the required reduction rates in levels of GHG production, and for building a healthy, equitable society for all.

Worldwide many governmental programs have been developed to reduce the environmental burden of personal vehicles. For example, the United States DOE operates a

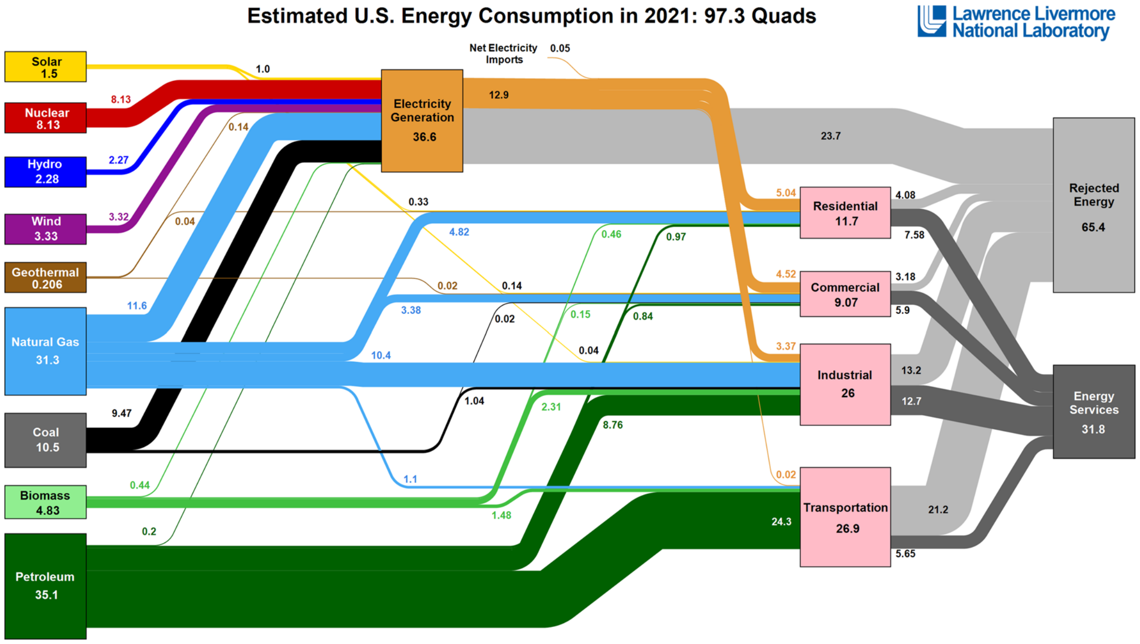

Fig. 2 U.S. DOE Sankey flow diagram of sources and uses of energy in the United States in 2021 [3]. CO_2 is generated by burning natural gas, coal, and petroleum for energy

Vehicle Technology Office in its Office of Energy Efficiency and Renewable Energy (EERE). It works closely with industry, academics, and other stakeholders to "build a clean energy economy that benefits all Americans." Its programs provide tools that the industry can use to reduce vehicle mass. Its 2019 Materials Vehicle Technologies Office Consolidated Report reports on a suite of 39 projects with a total federal investment of approximately $30 million, expended in the 2019 fiscal year alone. Its executive summary states:

"Because it takes less energy to accelerate a lighter object, replacing cast-iron and traditional steel components with lightweight materials such as advanced high-strength steels, magnesium (Mg) alloys, aluminum (Al) alloys, and fiber-reinforced polymer composites can directly reduce a vehicle's fuel consumption. By 2025, Materials Technology research activities seek to enable a 25% weight reduction of the glider for light-duty (LD) vehicles including body, chassis, and interior as compared to a 2015 baseline at no more than a $5/pound-saved increase in cost."

These projects are run with strong cooperation with industry, including industry and DOE project reviewers and evaluators with a bias to providing solutions that can be implemented in existing manufacturing plants with the current business model, cost structure, and rates of production. EERE also organizes technical road-mapping sessions, also with strong industry engagement. This is in addition to other federal investments in mass reduction programs at, for example, the Lightweight Innovations for Tomorrow (LIFT), a Manufacturing USA institute, and other programs on light metals and manufacturing from the National Science Foundation and other agencies.

However, is this forward-thinking, innovative strategy truly groundbreaking if the average vehicle 30 years ago met these weight reduction goals? Keoleian and Sullivan [9] state that: "Market trends in vehicle fleets in the past 2 decades have largely offset any gains in fuel economy from light-weighting. From 1987 to 2010, despite light-weighting initiatives, the average vehicle weight increased by 24%, because of growth in the sport utility vehicle (SUV) market share. Over the same period, horsepower increased by over 86%, and acceleration by 27%." Indeed, this may be the 'rebound effect' or Jevon's paradox in action, where efficiency improvements at the individual product level are offset by the growth in consumption and usage of materials [10].

This raises questions if by optimizing today's automotive design concepts, we are diverting attention from the design and implementation of bolder solutions that could be far more impactful with respect to reducing GHG production and improving society. Shifting the transportation paradigm beyond the personal automobile is actively discussed within fields such as urban studies and planning [11], but within the automotive design community, we see a very limited exploration of the available design space to radically cut emissions, while delivering the same, or better, service. Of course, bolder solutions will go beyond the technical and must include business models, consumer behavior, culture as well as technology. A first-principles analysis here suggests that future personal vehicles should be far different from current automobiles. Public transit, walking, and biking comprise the lowest-carbon solutions, and also promote the health and well-being of citizens, so should be prioritized when possible. However, some number of cars and light trucks will be crucial to a robust transportation portfolio, at least, to carry small groups of people and/or cargo over short distances where public transit, walking, and biking are not possible. These vehicles can and should be designed to be very efficient, long-lived, reparable, and adaptable.

We take a US-centric view in this work and adopt conventional units, as the US has one of the highest rates of CO_2 emissions [12] and energy use [13] per capita, the highest rates of vehicle ownership [14], and the largest cars, and is influential in setting consumption patterns across the globe. While each region is different in local details, the conclusions regarding vehicle design and manufacture should be relatively universal.

2 The Current State, Trends, and Design Constraints

It is instructive to note what is clearly changing, and what assumptions appear to be unquestioned with respect to passenger vehicle technologies. This context can guide the proposals of innovations bold enough to provide meaningful benefits, while sufficiently grounded to achieve commercial traction.

Electrification is clearly the focus of all upcoming and incumbent automobile manufacturers. The use of electrical energy, if generated by renewable sources can virtually eliminate GHG emissions from the vehicle use phase. While this provides an undeniable improvement to gas-powered vehicles, significant emissions arise from production [15]. It is estimated that the production of a typical EV battery for a small car, such as a Tesla Model 3, emits between 2.5 and 16 tons of CO_2 [16]. This is the rough equivalent of driving a 22 mpg vehicle between 7000 and 44,000 miles. In addition to decarbonizing the electricity grid, the impacts of materials production, from carbon intensity to water contamination and ecosystem damage, must be minimized.

Autonomy is another focus of automobile manufacturers and remains elusive despite large investments, and this is covered well in academic and popular literature [17]. It seems clear that autonomous vehicles will be available in the foreseeable future. True full, SAE Level 5 autonomy may allow a user to summon a driverless vehicle, greatly facilitating car sharing.

Features, size, and creature comforts have increased significantly since the fuel crises of the 1970s. Since 1980, the average vehicle weight in the US has increased from about 3200 pounds to over 4000 pounds. Average horsepower has increased from just over 100 horsepower to over 200 [18]. These trends seem to be amplified for electric vehicles. Table 1 shows many current electric vehicles, including their year of introduction and weight. The increasing mass requires additional embodied energy to fabricate and burns additional energy per mile. Larger and less aerodynamic vehicles also require greater power and larger batteries. Serrenho and Allwood [19] consider the impacts of both vehicle weight and electrification on CO_2 emissions, and find simply keeping vehicle mass low to be the most effective lever for minimizing CO_2 emissions, in the absence of an unexpectedly rapid decarbonization of the electricity grid.

Modularity or the use of standardized components, mechanical interconnects, and communication protocols is a concept that has significant and stable acceptance in the automotive industry. This allows the simple swapping of key components (batteries, infotainment, tires, sensors, etc.) using common protocols. In the 1960s and 1970s, automotive radios had standard geometric sizes, so the customer could select their own system and speakers. In recent times, this has been much better integrated into the automobile, with only marginal benefit. Standard modular batteries could be swapped at service, allowing the use of slower charging batteries, also possibly permitting the use of smaller battery packs, reducing vehicle mass, without range anxiety. This model has been pioneered by the failed startup Better Place [20]. Most importantly, standardized modules allow for swapping in new and improved components as improved batteries, vehicle sensors, and autonomous computational systems become available. This concept is closely tied to the repairability and 'right to repair' legislation that is currently under discussion in the popular media.

Lifespan or intensity of use of a vehicle is leading factor in controlling its overall environmental footprint. Validated data are hard to come by, but in the United States, it is typical for cars to be on the road for about 150,000 miles and

Table 1 Vehicle weights of several passenger vehicles

Vehicle	Year introduced	Weight (pound)
GM EV1 (lead acid batteries)	1996	3,086
Tesla roadster	2008	2,732
Tesla model S	2012	4,323–4,960
Tesla model X	2015	5,072–5,531
GM chevy bolt	2017	3,563
Tesla model 3	2017	3,552–4,072
Tesla model Y	2020	3,920–4,416
Ford Mustang Mach E	2021	4,394–4,890
Rivian R1	2021	6,949
Ford F-150 lightning	2022	6,015
Comparison, ICE: Honda Civic	2022 model year	2,877–3,102
Comparison, ICE: Honda Accord	2022 model year	3,300

12 years. At an average speed of 30 mph, this corresponds to about 400 h of use per year, meaning that a vehicle is parked for about 96% of its average life. Increasing the effective use of vehicles is a primary way to reduce the environmental impact of personal transportation.

Ownership models still favor the incumbent method of family-owned vehicles. In the United States, over 90% of households own or have access to a vehicle and over 20% of households have 3 or more vehicles [21]. For most of the US, owning a private vehicle is necessary to get to work, school, buy groceries, and engage with society broadly. This transportation model is a strong contributor to inequality in the US [22]. Car-sharing models are viable. However, outside dense urban areas, these models have not dramatically changed patterns of personal vehicle use (and have not improved access to transportation for disadvantaged populations [23]). The mainstream automotive industry has somewhat volatile sales patterns, but since 1980 there has been a general upward trend with the United States' annual sales of between 12 and 17 million new automobiles per year [24].

3 Design Principles and Goals

3.1 Design and First Principles Thinking

If a society is serious about combating climate change, modest changes in vehicle mass while adhering to the current usage model is not a credible approach. The principles of design thinking[25] are adapted where a desired outcome is stated and possible approaches to meeting this challenge are proposed and examined. Here, one possible design approach is developed with some detail, to the point its implications for lightweight manufacturing technology can be proposed.

We believe the correct design problem is: Can we develop a better method for personal point-to-point transportation for groups of 1–8 passengers that is:

- Convenient
- Affordable
- Safe
- Comfortable
- Efficient (in terms of user's time, and low GHG emissions/passenger mile)

3.2 Resulting Design Goals

The following are proposed as achievable and meaningful goals for the next-generation more sustainable vehicle. The driving attribute for this approach is the development of a far smaller fleet of vehicles that is much more heavily utilized, reducing the inefficiency represented by the 96% of cars parked at any one moment.

(1) *Long-lived and adaptable* The basic vehicle structure should be able to have a service life of over 2 million miles and 30 years, roughly a factor of 10 over the current vehicle mileage to retirement. If a vehicle is to last 30 years, we can predict with some certainty that the performance of many components will significantly advance over this period (particularly batteries, sensors, autopilot computer systems, and possibly motors). This is in alignment with the shearing layer model for buildings introduced by Stewart Brand [26]. Further, with standard sizes and interconnects batteries could be changed using the Better Place business model.
(2) *Highly-utilized* The design and business model target each vehicle being used at least 8 h per day. Again, this is nearly a factor of nearly 10 over current American vehicle usage.
(3) *Not personally controlled* In order to reach these levels of usage, the number of users per vehicle must increase significantly. This requires a shared vehicle usage model.
(4) *Lightweight* In this scenario, vehicles have a much longer life over which to amortize the use of premium materials and manufacturing methods. This offers a significant opportunity for mass reduction with methods now deemed too expensive.
(5) *Low aerodynamic drag* For speeds over 40 miles per hour, aerodynamic drag is a leading factor in power requirements. Reducing vehicle mass and drag allows for the use of smaller batteries and less powerful powertrains. These compounded effects are large [27]. Drag is not as important a consideration for an urban vehicle with on average low speeds.
(6) *Comfortable* Mass adoption is not likely to take place unless these vehicles are as (or nearly as) comfortable as a standard American passenger automobile.
(7) *Electric* Electrification provides a pathway for decarbonization in the use phase as the electricity grid decarbonizes, with significant co-benefits of reducing urban air pollution and noise. With a much smaller vehicle fleet, the impacts of electric vehicle manufacture and production will be reduced, and innovative techniques to reduce the impacts of metal extraction may be pursued.

3.3 Benchmarks

Adherence to these goals may allow dramatic decreases in GHG emission per passenger mile, but may lead to immediate questions such as: "Can such vehicles be manufactured, and business models deployed? Can such high mileage be withstood? Roughly what would it cost?" A cursory examination of some other passenger vehicles suggests this is very possible. Table 2 compares personal automobiles to other vehicles that see much more intensive usage.

The examples show that standard passenger vehicles (even those that are relatively aluminum-intensive, such as the F-150) have purchase prices of around $10/pound. This places some strong limits on the potential of exotic materials to make up a large fraction of the structure. The tractors for Class 8 over-the-road trucks are an interesting example. These are designed for over 1 million miles of usage and there is a clear economic incentive for mass reduction and efficiency as pounds saved, become additional pounds of cargo that can be carried, and the main cost of operation is fuel.

Subway cars are low-volume, high-duty vehicles where excess mass causes other system problems, such as excess wear of wheels and tracks, as well as increased need for power. The R179 serves New York City and 318 were commissioned. This serves as an important benchmark as subway cars have seen over 50 years of service and relatively high costs can be amortized over heavy-duty cycles.

Similarly, commercial aircraft have very high costs of production, where commercial benefits of reduced weight and increased efficiency are very high. The high demand use cycle and long life (up to 50 years [28]) demonstrate that business models can sustain the very high quality, safety–critical build demands.

Table 2 Cost, weight, and $/pound for a range of vehicles

Vehicle/example	Cost ($)	Weight (pound)	$/pound
Car: Honda Accord	29,000	3,102	9.3
Car: Ford F-150 XLT	41,800	4,465	9.4
Car: Tesla Model 3	42,990	3,552	12.0
Car: Rivian R1T	75,000	7,175	10.5
Class 8 Semi Tractor	200,000	17,000	11.8
Subway car: Bombardier R179	2,500,000	81,000	30.8
Helicopter: Sikorsky S-76D	15,000,000	7,005	2,140
Comm. Aircraft: ex. Boeing 737	106,000,000	90,170	1,175

4 A Specific Example

In 2010, the Progressive X prize was won by the Edison2 Very Light Car (VLC) [29]. The prize offered $10 million to any group that could build a production-ready vehicle capable of getting 100 mpg or its equivalent. The VLC won the mainstream class with 4 wheels and 4 seats and a lightweight internal combustion engine, which avoided the need for heavy batteries. The VLC is shown in the overview in Fig. 3. Its keys to success were its lightweight and aerodynamic efficiency. The aerodynamic efficiency is in turn developed by eliminating the shock-towers needed in conventional suspension (like a Formula 1 race car), by using an in-wheel suspension. This construction is provided in detail in Fig. 4. The design can also have very good crash performance. Crush space is available for head-on collisions, narrow offset front impact may be deflected, and the outrigger wheels can provide protection in a side impact.

This design concept is open-ended in that it can be scaled to larger sizes, and developed as a cargo-transport vehicle or larger numbers of passengers. The key concept is that there is a frame, wheels are on outriggers and the structure is fashioned to minimize aerodynamic drag, or compromise with other design objectives. Numerous specific designs and materials could be used, and the final design would almost certainly be multi-material with varied materials meeting specific local design objectives and variants are possible serving local needs. Edison2 has built and tested several variants since 2010, all show a roughly 40% reduction in mass and 40% reduction in aerodynamic drag versus traditional automobiles. This mass reduction immediately reduces the need for resources to create the structure and the reduced drag can enable smaller powertrains and reduced energy storage. This compounding of benefits reduces multiple environmental burdens.

Fig. 3 Overview concept of Edison2 Very Light Car (VLC) [29]

Fig. 4 Alternate construction details of the VLC, in particular showing how elimination of the shock tower can enable improved aerodynamics

Most importantly, the base vehicle structure, or glider, is adaptable to various powertrains, interiors, sensors, infotainment systems, and so forth. Accommodation can be made below, in front or behind the passenger compartment for batteries, which could be designed according to a standard for easy charging, or receptors for in-road conductive or inductive charging could be included. This standard modularity has several advantages. First, it allows regular upgrades of systems as improved ones become available or old ones run out. This is like the model that is used in Class 8 truck tractors where operators have the choice of several engines or radios that can be changed. Aircraft follows a similar model where engines, avionics, engines, and full interiors can be changed and upgraded. This is a clear example of the shearing-layer model [26] where over the life of a building varied components change at varied rates. The building site is the most stable, followed by the base structure that may be modified over time, skins are refreshed with new siding and possible insulation, services such as (Heating, Ventilation, and Air Conditioning) HVAC and communication are changed, and then the furniture and stuff change most quickly. Similarly, the base structure of a 737 may last 40 years, jet engines may be changed once, while hydraulics may see infrequent change, interiors may be changed every 5 years, and brakes and tires are changed several times per year. This shearing layer approach maintains the planned value of the key asset, while keeping components up to date. Of course, in the case of an automobile, this would require some standardization of the components for forward compatibility. The inclusion of easily swapped batteries may also allow this service on the road, allowing the use of smaller, lighter battery packs that would allow better vehicle efficiency without range anxiety.

The core of making such a model work would be the base structure that would be lightweight, aerodynamic, durable, and long-lived. Aircraft and Class 8 truck tractors show this is possible and indeed with such an approach, greater costs for the extensive use of lighter-weight solutions such as carbon-fiber composites and high-strength aluminum would be permissible as they would be amortized over a longer time. There is a counterargument that the current model-specific integration of systems allows better performance than the use of standardized components. Careful design studies would be required to understand the tradeoffs between standard and model-specific integration.

5 Implications

5.1 Manufacturing and Lightwighting Implications

One largely built version of Edison2 VLC is shown in Fig. 5. This highlights some of the key components that make up the glider structure. Bulkheads sit fore and aft of the passenger compartment and provide the primary structure that supports the other primary structural elements: the axle outriggers, crush zones, and frame rails. The bulkheads are the main structural features that transmit operational and crash loads across the vehicle.

At this stage of the vehicle conception, the design space has enormous degrees of freedom and many possible objectives to be optimized for. Optimization targets include: mass minimization, a vehicle that could be assembled near the point of use, longevity, the use of low-embodied energy materials, or the use of local materials. In the end, these choices are governed by the economic proposition, which depends on the market of deployment and the governmental policy in addition to the usual costs of capital and materials. Because design and manufacturing methods are being considered concurrently with the vehicle concept, the total design space is very large. This is a real opportunity, and the design space becomes wider as the number of manufacturing tools and materials, and component suppliers becomes larger.

A few design options for the VLC will be considered among a much larger set of options. The bulkheads are primary integrating elements and require good stiffness, strength, and ability to accept high-strength joints to axles, crash boxes, and frame rails. Construction options include cast aluminum or magnesium, better properties could be developed by forging, and carbon fiber-reinforced composites are also an option. The embodied energy of feedstock

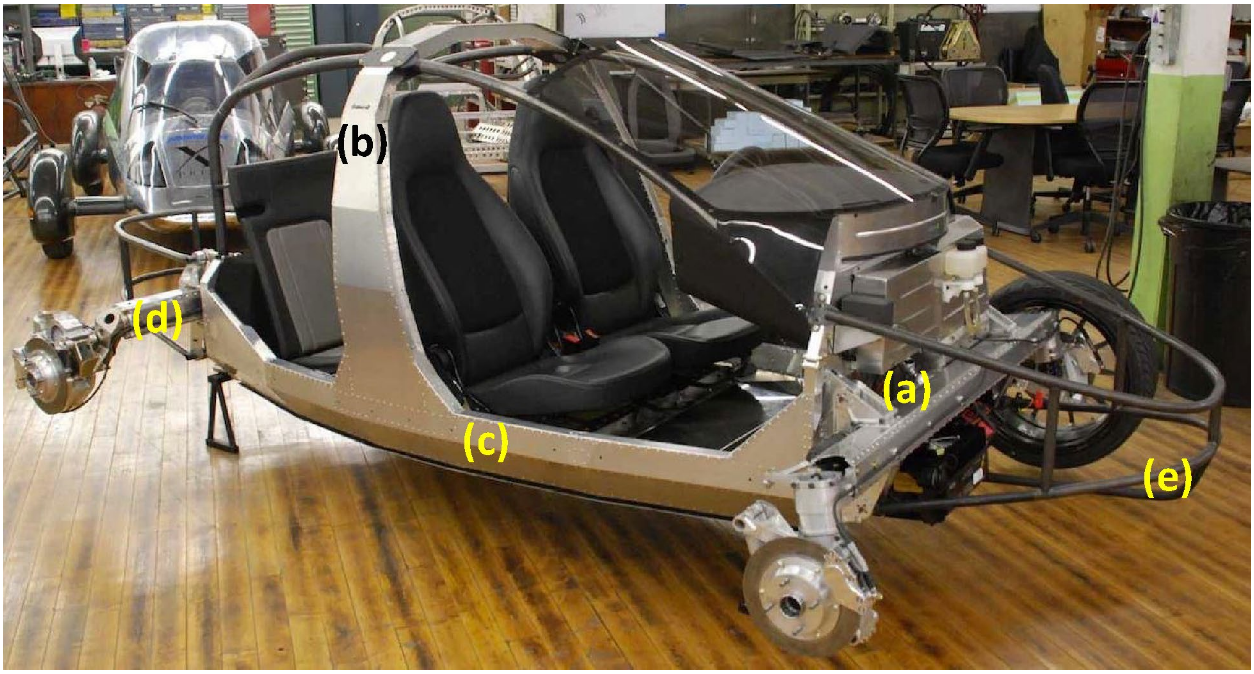

Fig. 5 Construction details of the VLC, showing: **a** front bulkhead, **b** roof frame structure, **c** frame rail, **d** outrigger axle and wheels with in-wheel suspension, and **e** crush zones

materials are subject to significant variations in CO_2- and energy intensity depending on technology age, processes, fuels, and electricity sources[9]. The sourcing of materials can significantly change impacts. These are integrated with other components that could be light metal extrusions, pultruded composite beams, or a composite monocoque. These elements must be integrated, and this would likely be by a combination of some sort of conformal interlocking features with welding, adhesives, or fasteners. There are numerous emerging technologies that can be important in all of this. For example, the bulkhead could be an aluminum plate upon which joining and stiffening features are added [30]. Rivets could be replaced by several types of solid-state welding [31] including impact welding, which has been shown to create very strong welds in fully age-hardened aluminum alloys without degrading temper or producing heat-affected zones [32]. The part count could be dramatically reduced by 'mega castings' [33] or possibly robotic blacksmithing [34]. Such large components could create most of the passenger safety cage.

The remaining skin structure and closure panels play a small role in crashworthiness and mostly affect aerodynamics, noise vibration, harshness, and aesthetics. Again, there are numerous manufacturing options, which need to be considered concurrently with product design. Stamping is the incumbent method, optimized for high-volume production. Lower volumes with metallic sheets are possible with hydroforming, superplastic forming, or incremental forming. Polymer exterior panels may also be sufficient. These could be thermoformed, with the possibility of integrating subsurface stiffening ribs. These approaches could be applied with pre-colored, preprinted, or decoratively wrapped exteriors. This could eliminate the vehicle paint shop, dramatically decreasing the carbon footprint of the manufacturing plant [35].

The final vehicle assembly can also be greatly simplified by proper attention to holistic construction methods. If the main body can be produced as a relatively small number of components to be assembled, this may be carried out near the point of use with a much smaller plant. That same facility may provide maintenance and upgrades. This could be important for reducing the carbon footprints associated with shipping and maintenance of large vehicle manufacturing plants, while providing resilience against shocks to global supply chains.

There are numerous options for the design and build of the system. Manufacturing programs such as those carried out by the DOE EERE VTO can provide useful options by validating components, and new manufacturing methods. This research may be of limited value for such new types of vehicles if it is too closely tied to incumbent vehicle design and manufacturing paradigms.

In terms of energy and carbon intensities, the manufacturing stage contributes a small fraction, 4%–5% of the lifecycle totals, but it can determine the efficiency of materials utilization [9]. For example, yield losses as high as 44% were found for sheet metal used in the production of passenger vehicles [36]. This is largely driven by simplifications made to accommodate a part for stamping, but implementing more flexible manufacturing processes can greatly reduce scrap rates. The paradigm here of a smaller quantity of higher-quality, higher-efficiency vehicles may justify alternative manufacturing processes, while also aiding more judicious use of potentially supply-limited materials such as lithium, copper, cobalt, and other essential rare earth elements. The transition to a smaller vehicle fleet will also bring about a large wave of end-of-life materials as the current fleet reaches end-of-life: principally steel, aluminum, and copper. In the current mode of assumed continuous growth, recycling end-of-life vehicles can make up only a fraction of the new fleet, even assuming technologies for closed-loop recycling, which are not the reality today [37]. However, by reducing future demand, the vast majority of material required for new cars may be met from old cars as well as be put to use for infrastructure and other goods, given investment in techniques to manage impurities [38] and meet increasing performance standards. Reducing throughput and creating higher-value, longer-lasting products may motivate the investment in materials processing technologies needed for true closed-loop recycling.

5.2 Societal Implications

Our transportation systems are systems that involve human behavior, business models, supply chains, physical constraints, legislative constraints, and much more. The model proposed here requires true systemic change with a proposal for far fewer, higher quality, longer-lived, more efficient personal transportation vehicles, as a part of a transportation portfolio that also enhances opportunities for walking, biking, and taking public transportation.

The systemic shift that results from our preliminary design study has multiple benefits:

(1) These vehicles can be far more efficient per passenger mile. The environmental costs of construction over the lifetime are cut by nearly an order of magnitude. The use of potentially higher-cost materials and manufacturing methods, along with right-sizing batteries, can minimize the energy used per mile traveled.
(2) Far fewer resource flows are needed, as this reduces dramatically the number of vehicles per person. The excess vehicles may be used to provide repurposed scrap steel to other projects without the need to mine and refine new sources. This model can ease the transition to new technology by reducing demand for supply-sensitive metals such as lithium, copper, and cobalt. Further, a sizable stock of steel, aluminum, and copper would become available by gradually retiring the current fleet of vehicles.
(3) Far less space is devoted to parking lots and structures. In the first comprehensive parking inventory in the US, it was found that in 4 out of the 5 cities studied, Philadelphia, Seattle, Des Moines, and Jackson had more parking spaces than households (in Jackson this ratio was 27:1) [39]. This strategy proposed here can improve pedestrian flow in both dense and suburban spaces. This has demonstrated improvements in the community, with less cruising for parking [40], and less air pollution, among other urban planning benefits. The land liberated due to the reduced need for parking could be turned into green space, which would on net consume CO_2. The size and height of larger vehicles have also been linked to the growing rate of pedestrian fatalities [41], a trend unique to the US amongst developed countries, which must be addressed.
(4) Employment and business patterns would change. Increased employment in vehicle maintenance, logistics, and upgrades could offset losses in the traditional vehicle production economy.

Changes such as those proposed here are truly systemic. Systemic changes are difficult to enact. It is not clear who should lead this change and how it would be enacted. Enacting the design goals here would dramatically reduce the annual rate of automobile production. This would face natural resistance from the companies that benefit from the incumbent models. This would also have to be driven by changes in consumer preferences. Consumers would have to see automobiles differently—not the high-horsepower, or luxurious points of personal pride, but instead as mechanisms to get from place to place without producing undue waste.

6 Conclusions

In view of the pressing challenges of climate change and greenhouse gas emissions, the current state of personal transportation is selectively assessed, and a conceptual design proposal is made that is actionable in the next 2 decades. Conceptual design goals are made for vehicles that are:

(1) *Long-lived and adaptable* a service life of over 2 million miles and 30 years.
(2) *Highly-utilized* > 8 h per day, on average.
(3) Not personally owned or controlled.
(4) Lightweight.
(5) Aerodynamic.
(6) Comfortable.
(7) Electric.

This model could reduce the environmental burden for vehicle production by about one order of magnitude, while improving per-mile efficiency. It would also change patterns of behavior opening parking lots and structures to new uses and opening jobs in vehicle maintenance and updating. A specific design approach based on the Edision2 Very Light Car is featured and it is noted that as the development and manufacturing of such a model is proposed, new tools may be needed for material shaping, casting, joining, and other base practices. Also new approaches may be needed to assess longevity and in inspection for damage.

Policymakers should be aware of the dramatic challenges that climate change poses and lead the implementation of bold actions that would avoid the worst outcomes of climate change. Incremental changes in current practice are unlikely to be sufficient. This is finding a local optimum in what should be considered as a much larger potential design space. Bold changes in the transportation systems are likely needed. This will be resisted by incumbent forces.

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Declarations

Conflict of interest Oliver Kuttner is an equity-holding principal of Edison2. GSD and KED have no financial interest in the ideas and research presented.

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