

The Energy Impact of U.S. Passenger Vehicle Fuel Economy Standards

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Abstract—Proposed fuel economy standards in the U.S. require new vehicles to achieve at least 34.1 miles per gallon on average by 2016. Scenarios of vehicle technology deployment indicate that this target is aggressive, requiring significant changes. New vehicles must become, lighter, smaller and a greater number will use advanced, more fuel-efficient powertrains. These changes can reduce fuel use, and also have implications on automotive material use and their corresponding production energy demands. This paper explores these effects to assess the energy impact of the fuel economy standards over time.

Index Terms—temporal life-cycle assessment, energy, vehicles

I. INTRODUCTION

THE Corporate Average Fuel Economy (CAFE) program has been regulating passenger vehicle fuel economy standards in the U.S. under the since the late 1970s. Today, the sales-weighted average new vehicle is required to achieve at least 25 miles per gallon (MPG). By 2016, the Federal government has proposed a more aggressive standard of 34.1 MPG.

The new mandate will cut the average fuel consumption of new vehicles by 20%. That will require significant changes in future vehicle offerings, including transitioning to alternative, more fuel-efficient powertrains and reducing vehicle weight and size. These changes involve use of alternative materials that tend to demand more energy to process, such as lithium-ion batteries in hybrid electric vehicles, or aluminum in lightweight vehicles.

In this paper, the auto industry's expected response to new fuel economy mandates will be examined, with the objective of ascertaining the resulting changes in auto material use, and determining the overall effectiveness of the CAFE program in realizing energy savings. Specifically, changes in auto material production energy and resultant fleet fuel savings for the entire U.S. passenger vehicle fleet, which are the main energy burdens in the vehicle's life cycle, are estimated.

II. PRIOR WORK AND THIS CONTRIBUTION

Previous analyses have examined how auto manufacturers could apply fuel-saving technologies to meet proposed CAFE standards. [1,2,3] Others have assessed the effectiveness of

CAFE program in reducing passenger vehicle fleet fuel use. [4,5] The impact on material production energy for the new vehicle fleet is understandably not included in these studies, since this is not an intended effect of the policy. This effect, however, is not trivial. For instance, the energy penalty in producing a hybrid-electric, or a plug-in hybrid-electric vehicle is +8 GJ or +24 GJ per vehicle respectively. Considering that sales of these vehicles are expected to increase, the upfront energy cost of creating a more fuel efficient vehicle fleet becomes significant.

Existing literature that consider the material production impact usually examine this on a vehicle level. Life-cycle energy and/or environmental assessments of new vehicle technologies have been carried out to compare individual vehicles. Some focus on vehicles with alternative powertrains [6,7,8], while others on the use of lightweight automotive materials. [9,10] Given the significant fuel savings accruing over the vehicle's long use phase, these studies conclude that it is beneficial to develop vehicles with greater fuel economy, despite reliance on energy-intensive materials.

Fleet-based life-cycle assessments (LCA) exist to consider the energy impact of *all* vehicles within the vehicle fleet, and not just a vehicle-to-vehicle comparison. [11,12,13] These studies arrive at the same conclusion as the vehicle-level LCAs, but the added temporal element offers insights on the timing of the expected benefit. The fleet-level LCAs, however, were carried out to assess the impact of reducing vehicle weight in particular, and none considered the impact due to other changes in future vehicles.

This study bridges the existing gaps in the literature to quantify the system-wide energy impact of CAFE program. By adopting vehicle life-cycle and fleet-level perspectives, this approach enables one to estimate the magnitude and timing of energy-saving benefit more accurately going into the future. The material production and use-phase energy impacts are both evaluated to understand the effect of weight and material composition changes in new vehicles entering the fleet each year. So this analysis reveals how much, how soon, and how energy savings can be achieved under the proposed fuel economy mandate.

III. METHODOLOGY

The study will examine the light-duty passenger vehicle fleet in the U.S., which consists of 250 million vehicles. A model of energy and material use in this fleet has been

developed, using the following approach:

- *Scenario analysis* is first used to evaluate the technologies adopted and plausible changes in vehicle characteristics and sales mix necessary to meet mandated fuel economy targets in 2016.
- *Automotive material demand* is assessed annually under the various future vehicle scenarios, based on vehicle sales and how vehicle material composition is likely to evolve.
- *Temporal life-cycle energy assessment* is done to capture the effects of evolving material and fuel use in the vehicle fleet, while accounting for efficiency improvements in materials processing, and reduced vehicle fuel consumption over time. This is done by modeling the stock of in-use vehicles by vintage.

The key outputs of the model are the material production energy demands and annual fleet fuel use in each scenario, which are the main energy burdens for this system. The energy associated with the fuel cycle, or well-to-tank impacts are not included. So the energy burden of charging plug-in hybrids is not within the scope of this study.

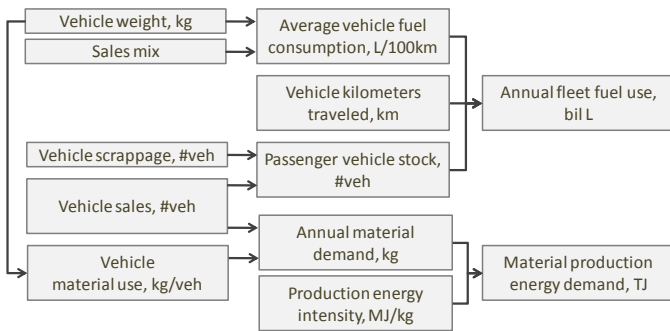


Fig. 1. Model overview.

IV. 2016 VEHICLE SCENARIOS

Scenarios of future vehicle sales mix and characteristics have been created that all meet the 2016 CAFE standard. These scenarios are not intended as forecasts, but a method to explore possibilities in an uncertain future. For brevity, only a few will be illustrated to emphasize different, near-term approaches to improving fuel economy:

A. Vehicle weight reduction – Weight savings can occur by using alternative lightweight materials, redesigning the vehicle to minimize weight, and eliminating features. Based on vehicle simulations, it is assumed that fuel consumption reduces by 0.4 L/100km for cars, and 0.5 L/100km for light trucks for every 100 kg weight reduction. In other words, for every 10% weight reduction, fuel economy increases by 6% for cars, and 8% for light trucks.¹

B. Vehicle size reduction – Size reduction involves shifting

¹ Powertrains are resized to maintain same acceleration performance when vehicle weight is reduced. Fuel consumption (or economy) refer to adjusted figures, which are revised upwards (or downwards) to better reflect actual, on-road figures, rather than dynamometer test results obtained in the laboratory.

sales away from larger, heavier and thus less fuel efficient light trucks, in particular SUVs, for cars. This reverses the trend of the past 20 years, where the market share of cars has been gradually diminishing (see Figure 2).

C. Introducing advanced, more fuel-efficient powertrains – Conventional internal combustion engines (ICE) are expected to continue improving in terms of fuel efficiency, with reduced friction and innovations like direct injection. The average fuel consumption of the new vehicle fleet can decrease further by introducing more turbocharged gasoline, diesel, and hybrid- and plugin hybrid-electric vehicles (HEV, PHEV). Figure 3 shows the lower fuel consumption of these alternative powertrains in cars, relative to the conventional gasoline ICE car today, which consumes 9.8 liters per 100 km (or 24 MPG).² The HEV modeled is a full hybrid similar to a Toyota Prius. The PHEV modeled has a 30-mile all-electric range. Given the near-term time frame of consideration, full battery electric vehicles will be excluded from the scenarios.

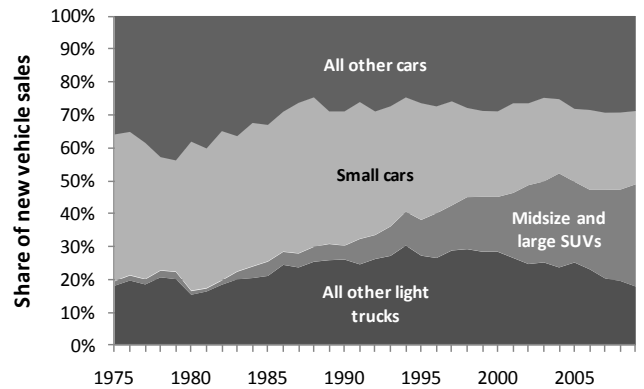


Fig. 2. Historical trend towards sport-utility vehicles (SUVs) in the U.S. (data source: [14])

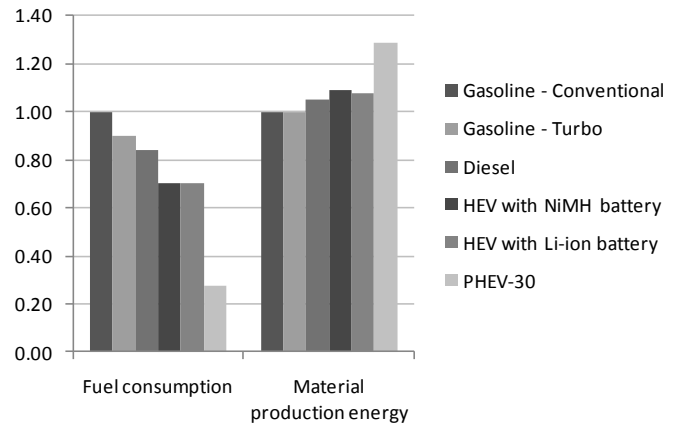


Fig. 3. Relative characteristics of 2008 vehicles, by powertrain.

Historically, almost all efficiency improvements in vehicles have been offset by improvements in horsepower and acceleration performance, rather than being realized in actual fuel consumption reduction. [15] For future vehicles in this analysis, it is assumed that this trend will reverse given more

² Diesel fuel consumption has been converted to gasoline equivalent.

Scenarios	Average new vehicle weight, kg	% cars (vs. light trucks)	% market share by powertrain					
			Conventional gas	Turbo gas	Diesel	Hybrid	Plugin hybrid	Total advanced powertrains
2008 = 27.0 MPG	1,720	53%	93%	5%	0%	3%	0%	7%
2016 average fuel economy = 34.1 MPG								
A. Lightweight	1,240	53%	93%	5%	0%	3%	0%	7%
B. Downsize	1,290	80%	93%	5%	0%	3%	0%	7%
C. Adv. powertrains	1,680	53%	22%	39%	13%	25%	1%	78%
D. Combination	1,460	60%	57%	21%	7%	14%	1%	43%

Table 1. Scenarios of the new vehicle fleet in 2016 that will meet the targeted 34.1 MPG average fuel economy.

stringent fuel economy regulation. There will be some improvement in performance in future vehicles, but not at historical rates. Half of future vehicle efficiency improvement will be dedicated to improving fuel economy instead.

Using this approach and these assumptions, four different scenarios are presented in Table 1, along with current (2008) figures for comparison. Each scenario is a snapshot of the new vehicle fleet in 2016 that will meet the mandate. The first three scenarios A, B and C are created by adjusting each variable – vehicle weight, size, market penetration of advanced powertrains – while keeping others constant, until the 34.1 MPG target is met. The final scenario D employs a combination of all three approaches. To constrain the solution space, the market shares of advanced powertrains in scenarios C and D are fixed at a ratio of Turbocharged gas : Diesel : HEV : PHEV = 3 : 1 : 1.9 : 0.1. This reflects a belief that more turbocharged engines will be employed since they are less expensive, and hybrids will outsell diesels in the U.S. market.

The scenarios illustrate the degrees of reduction in future vehicle weight and size, and the shift towards alternative, more fuel efficient powertrains in order to make the standard. They reveal that the proposed fuel economy standard is aggressive and would require significant changes starting from today. For hybrids to corner 14% of the market, as in scenario D, the annual growth rate is a high 27% p.a. The rates of deployment are challenging since automakers only have six years to meet the mandate.

V. PASSENGER VEHICLE FLEET MODEL

A sub-model is used to estimate the amount of fuel used annually by the vehicle fleet by tracking the stock of vehicles on U.S. roads, the distance traveled and their decreasing fuel consumption due to compliance with the CAFE standard.

Additional assumptions need to be made on future vehicle sales and scrappage. Vehicle sales dropped dramatically in recent years, and are expected to recover by 2016. Beyond 2016, the rate of sales growth is assumed to be 0.8% p.a., in tandem with expected U.S. population growth. Historical scrappage is derived from an estimated median vehicle lifetime of around 16 years [16], and a logistical function to estimate survival rate. Future scrappage is fixed at around 80% of vehicle sales. These sales and scrappage inputs, and the resulting growth in the stock of in-use or on-road vehicles are shown in Figure 4.

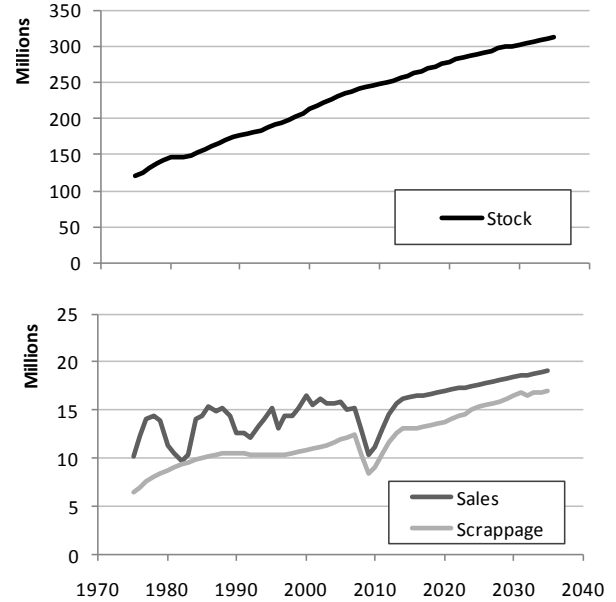


Fig. 4. Modeled U.S. passenger vehicle sales, scrappage and stock, 1975-2035.

VI. AUTOMOTIVE MATERIALS DEMAND AND PRODUCTION ENERGY INTENSITY

To ascertain the evolving energy impact of producing and processing automotive materials, one needs to estimate the material content in vehicles over time. The material breakdowns for historical and current conventional ICE vehicles are available from Ward's Communications (via [16]). That for a future lightweight vehicle is based on the European SuperLIGHT car concept [17], which relies mostly on high-strength steel and some aluminum to replace heavier iron and conventional steel within vehicles. The assumed material composition of future conventional vehicles, both gasoline and diesel, by degree of weight reduction is shown in Figure 5. To give context to this figure, the greatest degree of weight reduction portrayed in the scenarios is in Scenario A, which emphasizes lightweighting. In this scenario, the curb weight of an average new vehicle in 2016 weighs -480 kg, or 28% less than today.

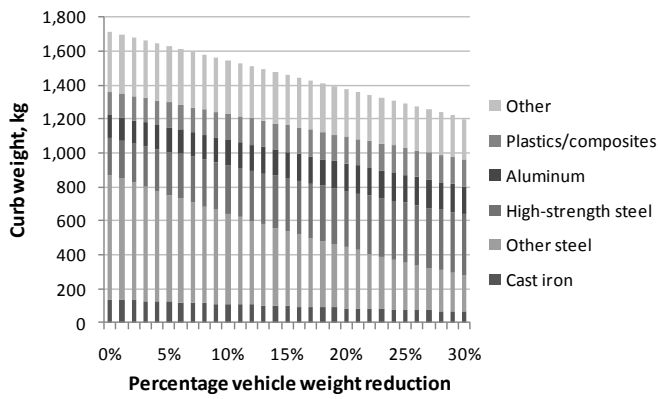


Fig. 5. Material composition of future lightweight vehicles.

The material breakdown of HEVs is based on Argonne National Laboratory's GREET 2.7 vehicle cycle model. [8] It is assumed that batteries in HEVs transition to be all made from nickel metal hydride (NiMH) today to all lithium-ion (Li-ion) by 2020, while the material breakdown of non-battery components remain constant over time. All PHEV batteries will be made of Li-ion. The Li-ion batteries of an average HEV, PHEV-30 weigh 23 and 135 kg initially, decreasing to 15 and 90 kg by 2020 as the energy density improves.

A comparison of the material composition of current vehicles with various powertrains is shown in Figure 6. Note that vehicles with advanced powertrains weigh more than a gasoline vehicle. For simplicity, it is assumed that the material breakdown is the same for all vehicle segments (cars, SUVs, and other light trucks). Material use per vehicle will scale with curb weight, depending on the scenario.

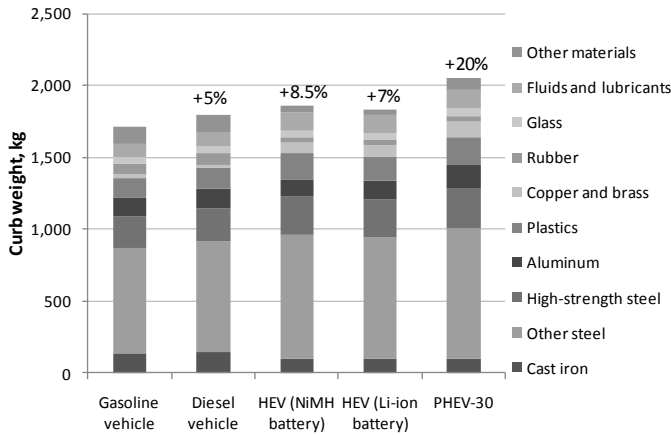


Fig. 6. Material composition of 2008 vehicles, by powertrain.

Next, the model attempts to capture the observation that material processing has and will become more energy efficient over time. The assumed primary energy intensities of producing ferrous metals and aluminum, which make up 60% of a vehicle's total production energy requirement, are shown in Figure 7. That for all other materials are assumed to remain constant for now. Data from the GREET model is used for figures for year 2000. Historical values are based on reports

commissioned by the U.S. Department of Energy. [18,19] Future values are based on industry targets. [20,21]. The relative energy impact due to producing materials used in current vehicles are shown in Figure 3. As mentioned, while vehicles with advanced powertrains consume less fuel, they use more materials and require more energy to produce. The material production energy impact per vehicle, however, is only around 6% of the energy expended over its long use phase in form of fuel consumed.

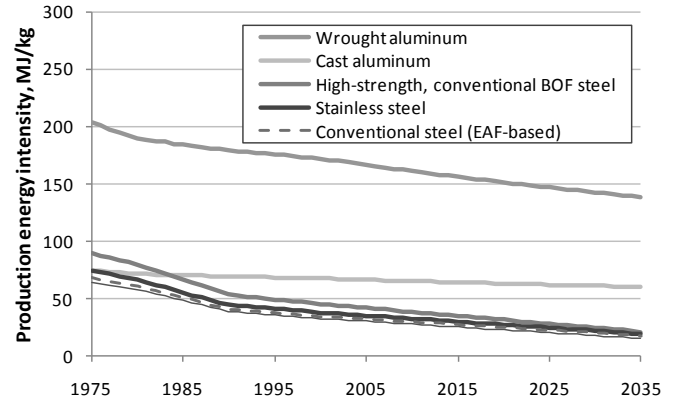


Fig. 7. Assumed energy efficiency improvements in material processing for select materials.

VII. RESULTS

We now have all the pieces necessary to infer the passenger vehicle fleet's annual fuel use, automotive material demand and corresponding production impact under the different scenarios. Results will be projected up to 2020, which include the effect of meeting the 2016 targets, and then fuel consumption and other vehicle characteristics remaining constant after. Under the different scenarios, we assume that changes in the vehicle fleet will take place in a linear fashion from today to 2016.

The fleet fuel use under the various scenarios that meet CAFE are similar, since the average new vehicle fuel economy in 2016 for all scenarios is the same 34.1 MPG (see Figure 8). This is compared against a "business as usual" baseline of unchanging fuel economy from today. Introducing the CAFE standards can realize cumulative fuel savings of 330 billion liters by 2020. Through 2020, fleet fuel use will not decrease, but will remain level despite growth in vehicle sales.

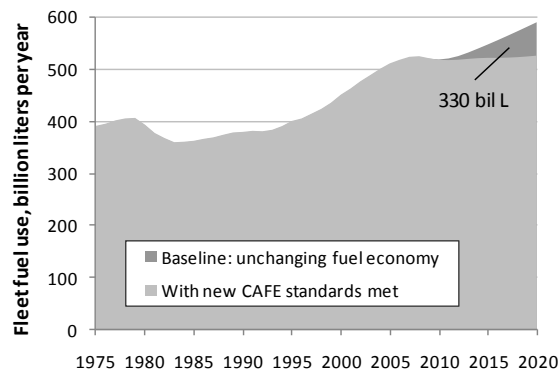


Fig. 8. Modeled U.S. passenger vehicle fleet fuel savings under the proposed CAFE mandate.

Introducing the CAFE standards will also influence automotive material demand, in particular that for the electrification of the vehicle fleet. Given the number of hybrid-electric vehicles required to meet the proposed standards, the demand for lithium and rare earth metals utilized in their batteries are expected to increase. Annual demand for these materials under Scenario D is shown in Figure 9. This chart reflects the assumption based on the GREET model that rare earths only appear in NiMH batteries, and are not utilized in other parts of the vehicle. As Li-ion batteries gradually replace NiMH batteries in hybrid vehicles, demand for rare earth metals will decline. Rare earths can also be applied in permanent magnets within electric motors, and estimates for the metal content in electric vehicles could reach up to 20 kg per HEV [22], and potentially higher for PHEVs. This has strong implications for the rare earth metals market, and is a suggested subject for further sensitivity analysis.

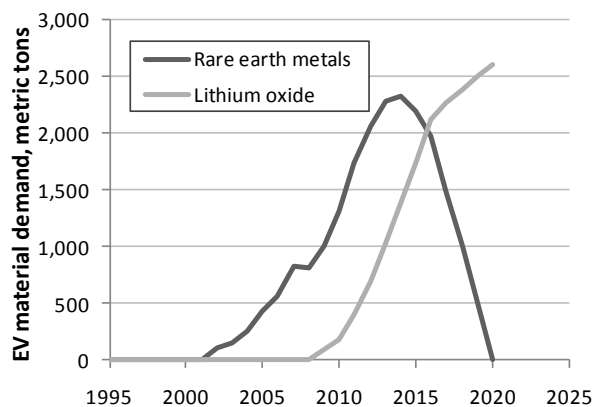


Fig. 9. Demand for materials used in hybrid-electric vehicle batteries under Scenario D.

The annual automotive material production energy demand measured in exajoules under the different scenarios is presented in Figure 10. This is the amount of energy required to produce/process materials embodied in new vehicles sold in each year.³ The historical impact tracks vehicle sales, as expected. Going forward, the demand levels despite increasing

³ Excludes materials in production scrap.

sales, as the effect of accounted efficiency improvements take place. The production energy demands for the four scenarios are observed to be similar. It is the highest for Scenario C, which employs more advanced powertrains that weigh more and require more energy to process. Pursuing a lightweight strategy thus implies a lower production impact, despite greater use of more energy-intensive aluminum. This result could certainly be influenced by alternative lightweight material pathways.

To isolate the effect of sales, material production energy demand per vehicle sold is plotted in Figure 11, for Scenario D only. The historical impact, in gigajoules per vehicle, tracks the weight of the average new vehicle sold. In the future, its decline can be explained again by efficiency improvements in materials processing, and due to the 15% average new vehicle weight reduction depicted in the scenario. The relative magnitude of these two effects is shown on the same figure by removing them in turn. This reveals that the material processing improvements are responsible for most of the decline in the production impact.

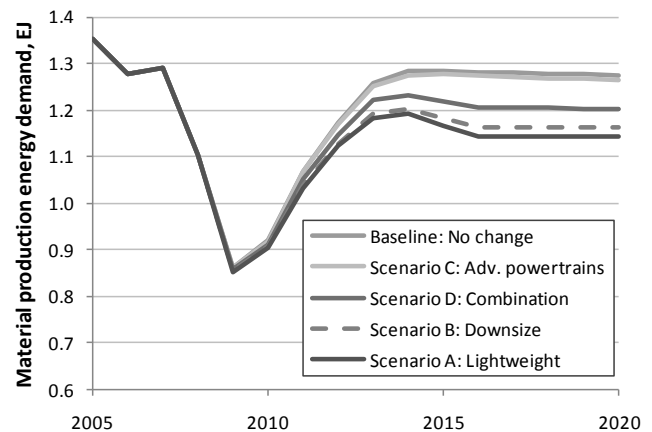


Fig. 10. Annual automotive material processing energy demand under different scenarios.

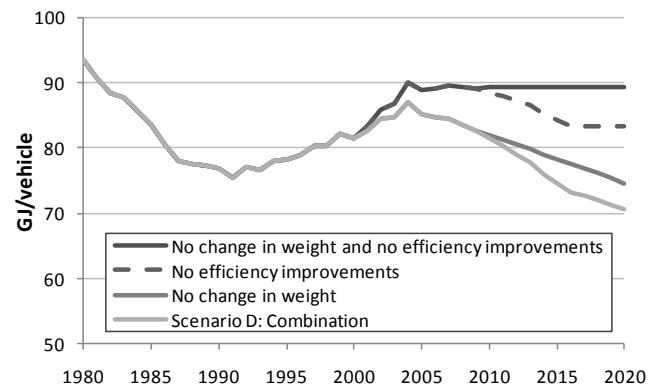


Fig. 11. Material processing energy demand per vehicle sold

VIII. CONCLUSION

By examining scenarios of future vehicle characteristics and sales mix, a model has been developed that enables one to (i) compare options to meet future fuel economy mandates on an

energy-basis, (ii) explore ways to reduce material production energy consumption by altering vehicle design or technology choices, and (iii) understand the implications on future automotive material demand. The key findings of this research are as follows:

- The proposed fuel economy standards for 2016 can realize significant fuel savings over time. They are, however, aggressive, and require rapid rates of vehicle technology deployment.
- Advanced, more fuel-efficient powertrains that are expected to dominate the marketplace, in order to meet the targets, are heavier and require more energy to produce. Their production impact may be offset by efforts to lightweight or downsize these vehicles.
- Efficiency gains in material processing over time can greatly reduce the production energy footprint of vehicles.

Further work is underway to explore various levels of fuel economy standards over different time frames, as well as alternative material pathways for vehicle lightweighting.

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