Life-Cycle Energy Savings Potential from Aluminum-Intensive Vehicles

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ABSTRACT

The life-cycle energy and fuel-use impacts of U.S.-produced aluminum-intensive passenger cars and passenger trucks are assessed. The energy analysis includes vehicle fuel consumption, material production energy, and recycling energy. A model that simulates market dynamics was used to project aluminum-intensive vehicle market shares and national energy savings potential for the period between 2005 and 2030. We conclude that there is a net energy savings with the use of aluminum-intensive vehicles. Manufacturing costs must be reduced to achieve significant market penetration of aluminum-intensive vehicles. The petroleum energy saved from improved fuel efficiency offsets the additional energy needed to manufacture aluminum compared to steel. The energy needed to make aluminum can be reduced further if wrought aluminum is recycled back to wrought aluminum. We find that oil use is displaced by additional use of natural gas and nonfossil energy, but use of coal is lower. Many of the results are not necessarily applicable to vehicles built outside of the United States, but others could be used with caution.

INTRODUCTION

U.S. automobile fuel economy, adjusted for vehicle size, has improved markedly since the two oil price shocks of the 1970s. Technologies responsible for improved fuel economy include fuel injection, front-wheel drive, improved engine aspiration (multi-valves/cylinder, turbo- and supercharging), transmission technologies (e.g., four-speed automatic with lock-up), improved aerodynamics, tires with lower rolling resistance, and increased use of lightweight materials. While many of these measures have already been used in production vehicles, the only area that promises significant improvements in fuel economy in the future (aside from development of totally new power plants and perhaps hybrid-electric vehicles) is the use of lightweight materials for body and chassis components.

Size-adjusted average vehicle weight has dropped slightly over the past two decades as a result of the use of plastics and cab-forward design [1]. However, if Corporate Average Fuel Economy (CAFE) standards are raised, or if oil prices rise sharply over an extended period of time, automakers will be faced with the need to further reduce vehicle weight. Downsizing is one option, but automakers are keenly interested in cost-effective, lightweight materials to reduce vehicle weight without sacrificing vehicle utility.[1] In addition, the zero-emission vehicle requirements will encourage automakers to produce lightweight vehicle structures to improve the range of electric vehicles. Based on current material and production costs and fuel prices, it is not economically practical to significantly reduce vehicle weight (by 20-30%) using lightweight materials.

However, a substantial amount of developmental work in lightweight materials is being pursued by major U.S., European, and Japanese automakers. While near-term benefits are not apparent, extensive use of lightweight materials in vehicles could have positive benefits over the long term.

In this paper, we estimate total life-cycle energy savings over time as aluminum-intensive vehicles (AIVs) penetrate the vehicle fleet.[2] Two sets of vehicles are characterized to compete with conventional material vehicles: (1) AIVs with limited replacement, providing 19% mass reduction, and (2) AIVs with a maximum replacement, providing 31% mass reduction. We assume that, by 2005, R&D will be successful in reducing the costs of manufacturing aluminum for vehicle structures (body and chassis). We assume the cost difference between a conventional vehicle and an AIV is due to the difference in materials costs. We do not analyze the potential for using lightweight materials in such components as glazing (windows) and interiors because they do not contribute significantly to the vehicle weight compared to the body and chassis. Future vehicles could have lightweight components not mentioned in this study.

The quantity of aluminum needed to replace steel in a mid-size passenger car is estimated using data available from auto manufacturers. These data are used to project the amount of aluminum needed to replace steel in other size classes. The improvement in fuel economy of the lighter vehicle is obtained by assuming the acceleration performance (expressed as the ratio of engine power to vehicle mass) remains constant, and that for every 1% of mass saved, fuel economy is improved by 0.66%. A vehicle choice model is used to project market shares of lightweight vehicles, assuming the cost of the vehicle increases as a result of the higher price of aluminum compared to steel. A vehicle survival and age-related usage model is employed to compute energy consumption over time. Life-cycle energy savings for the entire vehicle fleet is projected for the period between 2005 and 2030 for two fuel-price scenarios. To assess total energy use, the energy and fuels required to produce the materials, assemble the vehicles, and recycle them is estimated. We also consider the energy needed to extract, refine, and distribute the fuels. We combine life-cycle vehicle fuel consumption with the energy needed for vehicle production and recycling to assess national energy and fuel use impacts. Environmental impacts were notassessed.

VEHICLE MASS REDUCTION POTENTIAL

The desire to increase the fuel economy of a vehicle creates a significant motivation for reducing its curb (empty) weight. There are at least three ways to decrease the empty weight of a vehicle: (1) reduce its size, (2) optimize its design to minimize weight, and (3) replace the materials used in its construction with lighter mass equivalents. The third alternative, use of lightweight materials, has been pursued to some extent, but greater gains are possible. In addition to taking advantage of the lighter mass of aluminum compared to steel, further weight reduction is possible through parts integration and "holistic" design approaches, over and above what has been demonstrated in pure substitution exercises like the aluminum-bodied Mercury Sable developed by Ford. Incremental increases in the use of lightweight materials are predicted, at least through the early part of the next century [3].

Passenger Car Mass Distribution and Material Content -- An analysis of the mass distribution in a passenger car (according to component groups) shows that the body is the single heaviest group, with about 45% of total vehicle mass; the powertrain and chassis follow behind, in almost equal proportions (28% and 27%) (Figure 1). Within the body group, the unit-body, or body-in-white (b-i-w), is the single largest component, with about 28% of the total vehicle mass. Within the powertrain group, the engine is the single heaviest component, with roughly half the group weight, or about 14% of total vehicle mass, while the transmission represents approximately 5%. The chassis group, on the other hand, is not dominated by any single component; the wheels and tires are usually the single heaviest system, but they represent only about 6% of the entire vehicle mass.

The estimated material content in a typical American-made passenger car is shown in Table 1 [4]. The potential for significant weight reduction clearly involves replacement of the almost 68% of the mass constituted by ferrous materials. The single largest opportunity for lightweight material substitution lies with the b-i-w, which is made primarily from mild steel.

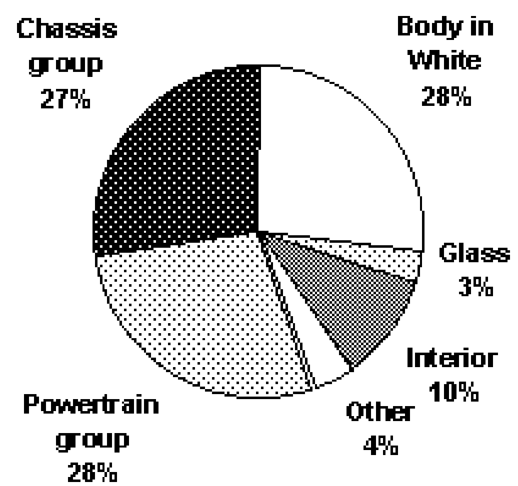

Figure 1. Passenger Car Mass Distribution

Mass Reduction Potential Using Aluminum -- Prototype aluminum-intensive vehicles based on mass-produced versions have been developed by most automakers.

One of the best-documented examples is the aluminum-body Mercury Sable developed by Ford. The vehicle is part of a design and production study aimed at evaluating the feasibility of a stamped-aluminum body process for mass manufacture of passenger cars [5]. The approach was to replace the material (i.e., use aluminum-alloy sheet instead of steel), while maintaining the current vehicle design (a 1993 Sable) and using basically the same body-manufacturing process (spot welding and bonded sheet-metal stampings). The mass reduction achieved for the body was 173 kg; about 47% less than the equivalent steel body. A comparison of the mass of individual key components as produced by using both materials is shown in Table 2 [6].

In addition to the mass saved with the aluminum body, other changes in the powertrain and chassis (allowed by the lower mass of the body) could have resulted in a further reduction of about 90 kg, for a total mass reduction of about 20% compared to the standard steel-intensive Sable. Therefore, use of aluminum for the body plus secondary weight savings could turn a 1,429-kg, four-door, mid-size sedan into a 1,152-kg-curb-weight vehicle. This reduction in vehicle mass translates into a fuel economy improvement of about 12.5%, or to a projected combined (city/highway cycle) U.S. Environmental Protection Agency (EPA) mileage increase from 10.7 to 12.0 km/L. We investigated other examples of using aluminum instead of steel. In all cases, the conclusions were similar in aluminum body results in a mass reduction of 40-47% over the comparable steel body, even when the design follows steel practice (i.e., the design of the vehicle is not completely optimized for aluminum manufacture).

Aluminum concept cars, of which there have been several examples recently, are free from the constraints of a previously designed steel vehicle. The Ford Synthesis 2010 is one of the better-documented aluminum-intensive, stamped-body concept cars. Synthesis 2010 has the same interior dimensions as a Taurus/Sable and is designed to carry a similar payload, but it has a curb weight of only about 1,043 kg (about 386 kg less or almost 27% lower than the 1,429-kg comparable steel vehicle). However, the Synthesis vehicle is powered by a 60-kW, two-stroke, aluminum engine, which is undoubtedly much lighter than the standard Taurus/Sable power plant. Still, the differences in mass savings between the aluminum Sable and the Synthesis indicate that there is indeed a somewhat higher potential for a lightweight vehicle that is designed from the beginning as an aluminum-intensive concept.

The stamped-sheet, spot-welded, aluminum body is not the only concept currently vying for replacement of the conventional steel passenger-car body. The other aluminum-intensive passenger-car concept is the space-frame. Because the mass, strength, and rigidity of the aluminum space-frame passenger car body appear to be similar to those of the stamped-sheet and spot-welded equivalent, we used the stamped-sheet, spot-welded, aluminum body for our analysis. In this study, we do not assess the potential of radically new forming methods, such as superplastic forming, for lowering costs.

Experience with practical substitution of steel with aluminum shows that in components designed primarily for rigidity, as in the b-i-w, 1 kg of aluminum replaces between 1.66 kg [7] and 1.87 kg [8] of steel. On the other hand, in components that are designed primarily for strength, as in many chassis parts, 1 kg of aluminum replaces about 2 kg of steel [9]. In cylinder heads, designed primarily for strength, the ratio is also about 1 to 2, while in cylinder blocks, where rigidity is also important, the ratio is about 1 to 1.7. In simpler castings, where geometry is governed by process rather than strength or rigidity (minimum cast thicknesses are larger than actually needed), the ratio is equal to the density ratio (i.e., 1 kg of aluminum replaces about 2.7 kg of cast iron). Aluminum has very high specific energy absorption, so it is not too difficult to make structures designed for rigidity that also meet safety (impact) requirements.

Our scenarios for AIVs are based on information available in the literature and on discussions with automakers. We assess two types of AIVs: (1) those with a b-i-w made of aluminum (e.g., Mercury Sable AIV) and (2) those for which aluminum castings are used extensively in addition to an optimized aluminum b-i-w (e.g., Synthesis 2010, excluding the effects of the two-stroke engine).

We call the first type AIV-Mid, and the second type AIV-Max. Table 3 summarizes the weight reduction potential for the two types of aluminum mid-size vehicles compared to the typical mid-size vehicle described in Table 1, using the substitution ratios described above. Secondary weight reduction is estimated to be about 50% of primary weight savings [5, 10].[3] For the AIV-Max type, we assume the engine size and power rating are reduced to maintain the same power-to-vehicle weight ratio as the conventional vehicle.

PROJECTED COST OF SIGNIFICANT MASS REDUCTION USING ALUMINUM

Volume-produced passenger cars are truly a bargain. In America, the typical family sedan can be purchased at the dealer's lot for about $11.00/kg (all dollars are in U.S. currency). Such a vehicle is sold wholesale by the automaker at about $9.30/kg, and it comes out of the assembly plant at the direct cost of about $5.00/kg. Manufacturing cost includes roughly $3.00/kg for labor and plant overhead and about $2.00/kg for materials, (including value of offal). Currently, about 68% of the mass of material used in the typical passenger car is represented by iron and steel, which are purchased at a cost of only $0.77 to $1.20/kg. Even considering that a pound of steel is replaced by a lesser amount of a lightweight substitute, it is clear that, to maintain current manufacturing costs, the maximum cost of any replacement material cannot be much above $2.20/kg. Aluminum sheet (the type needed for a stamped/welded body) sells for an average of about $3.30/kg. Therefore, unless significant labor and overhead savings are involved in fabrication of lightweight vehicles in high volumes, there will be significant increases in vehicle costs. (However, total cost to the consumer could be lower because of improved fuel efficiency and perhaps longer life.)

The process for manufacturing a stamped-sheet aluminum passenger-car body is not much different from that used to produce a steel body. The aluminum is formed in the same type of presses, using very similar dies. Aluminum sheet, in general, does not form as well as steel, so for highly contoured panels, an extra strike (and an additional die) may be necessary. Aluminum is far softer than steel, so it has to be handled with greater care to prevent scratches, especially on A-class panels. None of these factors is going to make aluminum cheaper to form than steel, although the difference will not be that great either. Aluminum is a much better conductor than steel and is therefore harder to spot weld (it requires much higher current) and demands greater separation between welds. On the other hand, aluminum bodies will likely rely more on adhesive bonding and less on spot welds than equivalent steel components, so fabrication may be more or less the same after all. Still, it is expected that stamped-aluminum-body manufacturing will require as much as 10% more labor than the equivalent steel process. All these factors point toward greater costs to manufacture a stamped-aluminum body than its steel equivalent. If we assume that R&D; lowers the labor and capital cost (per vehicle) of an AIV to that of the steel baseline vehicle, the only cost difference is that of the material itself, with proper accounting for scrap. We estimate that the incremental price (manufacturers suggested retail price [MSRP]) of the AIV-Max vehicle would range between $1,100 and $1,300, depending on assumptions about overhead rates and other factors [2]. For the market penetration analysis, we use an incremental price of $1,200. The incremental price of the AIV-Mid vehicle, calculated in a similar manner, is assumed to be about $800.

MARKET PENETRATION POTENTIAL OF ALUMINUM-INTENSIVE VEHICLES

***Model Development* --** Argonne National Laboratory (ANL) characterized a set of vehicles by using data from the above mass reduction and incremental cost analysis. A vehicle choice model was executed under two fuel-price scenarios for both the AIV-Mid and the AIV-Max technology vehicles, and a vehicle survival model was used to simulate impacts on on-road fuel economy and energy consumption. The vehicle choice model, a component of ANL's Transportation Energy and Emissions Modeling System (TEEMS), has been used in many studies [12-14]. Based on the work by Lave and Train [15], the model has undergone several changes and has been updated twice [2,16].

Market penetration of various sizes of light-duty vehicles was simulated for the years 2005, 2010, and 2030. The simulated market shares, together with the historical new light-duty vehicle sales by size [17] were used in a separate model to estimate registration, vehicle miles of travel (VMT), and energy use. The four-stroke gasoline-powered engine was assumed to improve over time by using multi-valves, electronic controls, overhead cams, intake valve control, and accessory modifications. We assumed that improvement in the use of such conventional materials as steel would result in some reduction in vehicle weight even without any lightweight materials.

Fuel prices projected by the U.S. Energy Information Administration (EIA) in its 1993 Annual Energy Outlook [18] are used for the first scenario, the Reference Fuel Price Scenario. Motor fuel prices increase 0.9% annually during 1990-2005, from $9.35/GJ to $10.72/GJ (1991 dollars), and 1.3% annually after 2005. A second scenario involving higher fuel prices was developed to evaluate changes in vehicle choices under such prices. Past experiences of higher fuel prices were evaluated for this purpose. The High Fuel Price Scenario assumes fuel prices would rise by 40% compared to the Reference Fuel Price Scenario. We found that fuel demand does not change significantly for a fuel price rise of 40% as changes in fuel cost per mile are not dramatically different and the competing vehicle attributes were kept unchanged. In this paper, we discuss only the Reference Fuel Price Scenario; details of both scenarios are discussed in a previous paper by the authors. [2]

Three versions of each size automobile, three versions of minivan/small utility vehicle, and one version each of small pickup, standard pickup, and standard van/large utility vehicles were characterized. A version typically represented a conventional material vehicle with market-oriented fuel economy, a vehicle with limited aluminum substitution (AIV-Mid), or a vehicle with maximum aluminum substitution (AIV-Max). All four sizes of automobiles and minivan/small utility were candidates for aluminum substitution. The extent of aluminum substitution determined the changes in such vehicle characteristics as price, curb weight, andoperating cost per mile. Vehicle performance, in terms of power per pound, was kept unchanged from 1990 in all cases. The various versions characterized for the analysis are described in more detail in our earlier paper [2]. Figure 2 shows the weight reduction potential of a mid-size conventional steel vehicle and mid-size AIVs over time. Figure 3 shows the corresponding fuel economy.

To determine the market impact of AIVs, three cases were analyzed. A Base Case assumes that no material substitution occurs. The other two cases include AIVs competing with the conventional material vehicles. The vehicle menus for these cases are described as follows.

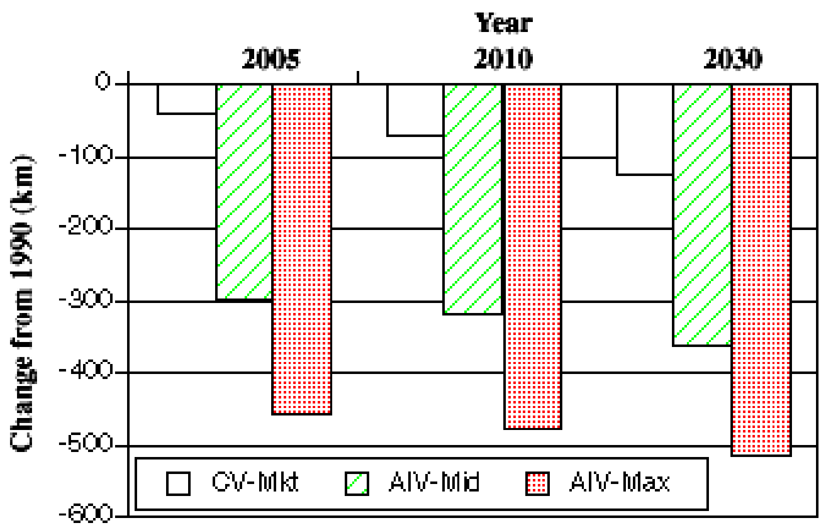

Figure 2. Weight Reduction Projection: Mid-Size Car

1. No Substitution (Base) Case: The vehicle menu for this case consisted of conventional-material vehicles with market-oriented fuel economy (CV-Mkt). Eight vehicles (four cars and four trucks) were analyzed.

2. Mid-Tech Aluminum and Conventional Material Case (AL-Mid): The vehicle menu for this case combined vehicles from CV-Mkt and AIV-Mid types. Lightweight-material vehicles were offered along with conventional-material vehicles, expanding the number of vehicles in the menu. Three AIV-Mid vehicles (mid-size car, large car, and the minivan/small utility) were introduced beginning in 2005. An AIV-Mid compact car was introduced beginning in 2010.

3. Max-Tech Aluminum and Conventional Material Case (AL-Max): The vehicle menu for this case combined vehicles from CV-Mkt and AIV-Max versions. Both conventional-material vehicles and AIV-Max types were included, expanding the Base Case vehicle menu. The AIV-Max types of mid-size and large cars and the minivan/small utility were introduced beginning in 2005. An aluminum compact car was added beginning in 2010.

Market Penetration Results **--** A significant market for lightweight vehicles is possible given our assumption of an incremental cost of $1,200 for a 460-kg weight reduction. Figure 4 shows the market penetration for the AIV-Max type. Assuming the AIV-Max is first mass-produced in 2005, its market share of new vehicle sales increases to 33% for cars and 26% for mini-vans and small trucks by the year 2010. In 2030, the market for aluminum-intensive cars rises to 42% given our assumption that manufacturers will introduce aluminum in a broader size class by then. The new vehicle sales data form the basis for the national energy savings estimates discussed later.

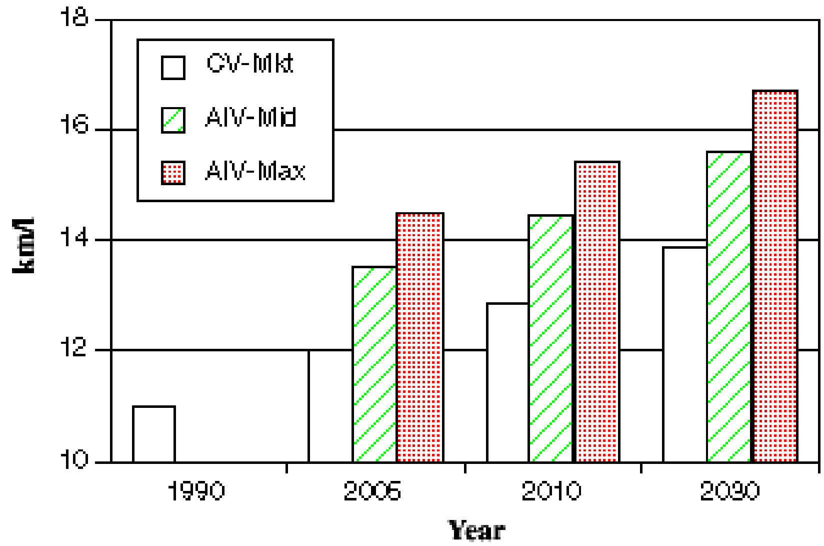

Figure 3. Fuel Economy Projection: Mid-Size Car

ENERGY REQUIREMENTS FOR PRODUCTION AND RECYCLING OF AUTOMOTIVE MATERIALS

Automobiles consume fuel to perform their transportation function, but energy is also consumed for their production. Lighter cars consume less fuel over their lifetimes, but the energy required to produce the materials the cars are made from may increase, offsetting the fuel economy gains. However, the materials in the automobile are available for recycling at the end of the vehicle's life and can displace virgin materials, generally with reduced energy inputs. Therefore, we assessed the energy required for production and recycling of the automobile materials so that the total lifetime energy consumption can be estimated.

After automobile parts have served their intended uses, there are several alternative paths for material disposition. These paths include (generally, but not necessarily, in order of decreasing energy saved) reuse, recycling, combustion with or without energy recovery, and landfill. Recycling can either be closed loop (recycling to the same product) or open loop (recycling to another product). The energy saving that can be credited to recycling to other products is equal to the energy displaced -- the energy that would have been required to supply that product in the usual way. If the other product is lower in value or embodied energy, the term "downcycling" is sometimes used. Material that is not recycled to recover material values can be burned for its energy content in a waste-to-energy plant. (We do not consider this option in our analysis.)

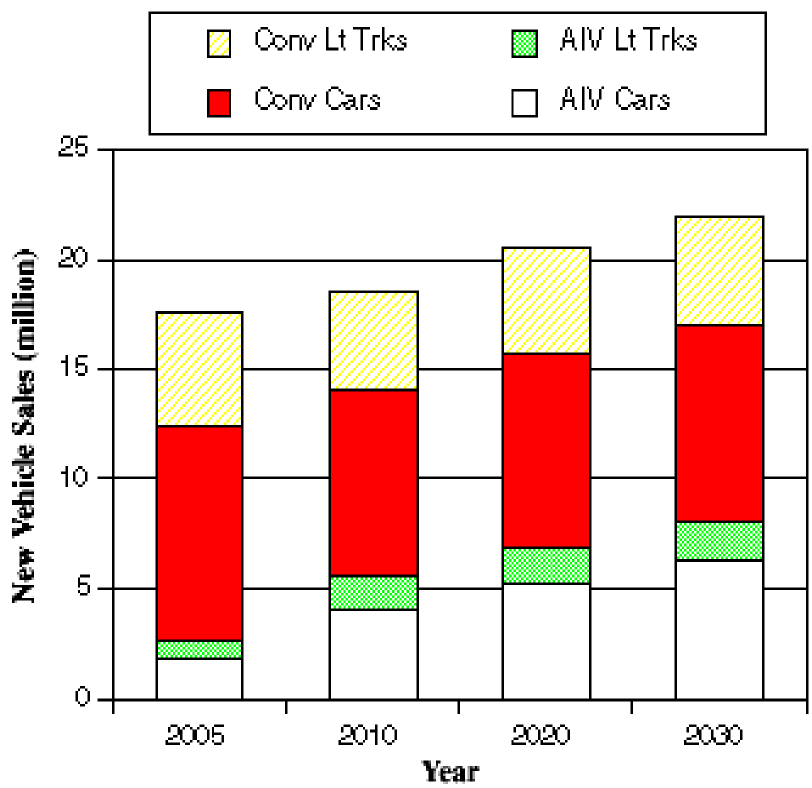

Figure 4. Market Penetration of Aluminum-Intensive Vehicles By Size (Base Fuel Price Scenario)

Production of metals is very energy-intensive because the ore must be mined, concentrated, and subjected to endothermic chemical reactions to yield the metal product. Recycling is generally less energy-intensive because the basic material only needs to be remelted. However, in either case, the basic metal product requires fabrication, which is moderately energy-intensive, to give a final product. Therefore, the energy required to recycle is substantial, but still considerably less than that required to produce virgin material, and recycling of metals does conserve energy. Steel and aluminum production and recycling energy and fuel mix is discussed in more detail below. We assume the energy intensity and fuel mix do not change significantly from current values. A more detailed analysis is required to assess the impact of changes in fuel mix and material production technology. Tables 4 and 5 summarize values used for materials-related energy consumption and purchased energy mix, respectively. The fuel mix, including the fuels used for electricity production, is shown in Table 6.

Steel **--** Total energy for production of auto parts from virgin steel sheet is about 65 MJ/kg and for recycled production is about 52 MJ/kg [19]. In current practice, auto sheet is recycled into the general body of steel going to all uses; the general body of steel embodies the same amount of energy as auto sheet. In the future, if cross-contamination of alloys becomes a problem, it would make sense to recycle it back to sheet. The savings from steel recycling are not nearly as dramatic as those for aluminum recycling, because the total energy for virgin steel production is so much lower than that for aluminum. Therefore, the total energy for production of automobile materials will not be affected significantly by increasing the already large quantity of automotive steel recycled. Shifts to other types of steel will affect the energy use more by decreasing the total mass of material than by changing the unit energy requirements, because production energies for the different types of steel are similar. In the future, the production process for pig iron may change to direct reduction, with some energy savings. The mix of fuels used in production of steel sheet products is shown in Table 6. Note that over half of the energy for virgin sheet production comes from the coal used to produce coke for the blast furnace [21].

Cast Iron **--** Cast iron parts for automobiles are generally produced by automakers in their own foundries, using scrap iron and steel as the raw material. Scrap is reduced in size by shredding, shearing, cutting, or crushing, depending on the source, and charged to a cupola furnace, which resembles a small blast furnace. Foundry coke, similar to metallurgical coke but slightly more energy-intensive, supplies the heat to melt the metal, which is then poured into molds. The total energy required for gray iron castings is about 37 MJ/kg, mostly in the form of coal for coke production [19]. Because cast parts are already made from recycled material, no estimate is made for production from virgin pig iron. Note that offal rates affect the energy use for cast parts significantly, because rejected material must be melted again. Therefore, techniques like near-net-shape casting can significantly decrease energy use per part shipped.

Wrought Aluminum **--** The total energy for virgin produc-tion is about 231 MJ/kg and for recycled production is about 52 MJ/kg [19]. Energy use for extruded products is slightly lower because of lower scrap rates. The large difference is due to the high energy requirement for reduction of alumina (Al2O3) to elemental aluminum metal. Most of the energy for both virgin and recycled processes is in the form of electricity from fuel sources and hydroelectric power. The energy for recycling has been estimated assuming no metal loss in the recycling loop. Losses would require replacement by energy-intensive virgin material; a 10% loss rate raises the energy required to produce 1 kg of recycled aluminum products to 68 MJ. One source reported 6.9% aluminum loss in shredding and 5.8% in casting, implying the need for 1.14 kg of old aluminum to produce 1 kg of recycled aluminum [22]. However, more recent practices may have improved material-recovery rates. The mix of fuel purchased is shown in Table 5, where it can be seen that 4% of purchased energy is from coal, 12% is from oil, 34% is from natural gas, and about 50% is electricity (20% hydro and 30% non-hydro). If the fuels used for electricity production in regions where primary aluminum smelters are located are considered, about 50% of the fuel mix is coal (Table 6) [23].

Cast Aluminum **--** Aluminum castings are produced mostly from recycled material and therefore have a lower average embodied energy than wrought products, which are made from virgin raw materials. Therefore, the usual argument that aluminum is very energy-intensive and use of aluminum in autos drives up the production energy is not entirely correct. When recycled material can be used, the energy per pound is comparable to that of steel, and the energy per part is actually lower. It is estimated that 80% of the aluminum used in cars today is recovered from scrap [24]. The energy embodied in 1 kg of cast aluminum parts is about 44 MJ [19]. Aluminum scrap is melted in large gas-fired reverberatory furnaces.Alloy compatibility is a major concern in producing good quality parts from recycled materials. In current practice, the smaller quantities of wrought aluminum auto parts are recycled into the larger mass of castings, and undesirable elements are diluted. However, if the quantity of wrought auto parts rises significantly, dilution may become impractical, and segregation of parts during recycling would become desirable.

Vehicle Assembly and Dismantling Energy, Recycling Assumptions, and Total Energy Use **--** The energy required for production and recycling of other automotive materials is summarized in Table 4. The purchased fuel mix for each material is shown in Table 5. In addition to the energy needed for material production, energy is needed for vehicle assembly and vehicle dismantling. DeLuchi [20] estimates about 3.8 MJ/kg (vehicle weight) is required for assembly, primarily in the form of electricity. We assumed vehicle dismantling for recycling or disposal requires 1.1 MJ/kg in the form of electricity, based on energy required for a materials recovery facility [25]. We did not consider other material recovery processes like pyrolysis, nor did we consider combustion for energy recovery.Three recycling scenarios were considered: (1) material that can be recycled is used again in vehicles; (2) no material is recycled; and (3) scenario 1 with the change that wrought aluminum is recycled to cast aluminum. The recycling rates we assumed for scenario 1 are listed in Table 7. We also assumed the recycling rate for most materials increases between 2005 and 2030. These values are currently not achievable and are considered targets. As seen below, the assumptions on recycling rates do not significantly influence our conclusions.

To account for the full fuel cycle, we included the energy use prior to final conversion in the vehicle. This included extraction, refining, and delivering the fuel, or primary energy. Table 8 summarizes the net energy available after these steps.

LIFE-CYCLE PRIMARY POTENTIAL OF ALUMINUM-INTENSIVE VEHICLES

Results are presented first on a per-vehicle basis using the mid-size passenger car and year 2010 as an example. Next, national energy savings are projected over the period 2005 and 2030 for the entire light-duty vehicle fleet using results from the market-penetration analysis.

Life-Cycle Primary Consumption of Mid-Size Passenger Cars **--** The conventional vehicle consumes about 867 GJ of primary energy as fuel over its lifetime. The AIV-Mid vehicle, weighing 19% less, consumes about 759 GJ or 12.5% less primary energy than the conventional vehicle (Figure 5). The AIV-Max vehicle, weighing 31% less than the conventional vehicle, consumes about 690 GJ, or 20% less primary energy than the conventional vehicle. (This conclusion assumes the AIV travels the same distance over its lifetime as the conventional vehicle. For the market-penetration analysis, we assume AIVs are more durable than conventional vehicles; therefore, their lifetime miles are greater than for the conventional vehicle. This assumption affects the market penetration and national energy saving estimates.) The primary energy embodied in the materials and manufacturing process for both conventional vehicles and AIVs is relatively small compared to the primary fuel energy consumed by the vehicle. For the conventional vehicle under the maximum-recycling scenario, the materials and manufacturing primary energy is about 79 GJ, equivalent to only about 8% of the primary fuel energy consumed. For the AIV-Mid vehicle under the maximum-recycling scenario, materials and manufacturing primary energy is about 66 GJ, or about 9% of the primary fuel energy consumed.

As expected, the embodied primary energy of the aluminum in the AIVs is much greater than the embodied primary energy in the other materials. The wrought aluminum in the AIV-Mid vehicle contains 26 GJ of embodied primary energy, or about 40% of total vehicle materials energy (assuming none of the aluminum is recycled back to wrought alloys in 2010, because at that time, AIVs will not have yet been scrapped for recycling). Recycling wrought aluminum back to wrought aluminum is beneficial; after AIVs are scrapped and wrought aluminum is recycled to wrought aluminum, the embodied primary energy in the AIV-Mid vehicle drops from 26 GJ to 13 GJ (assuming 93% is recycled).

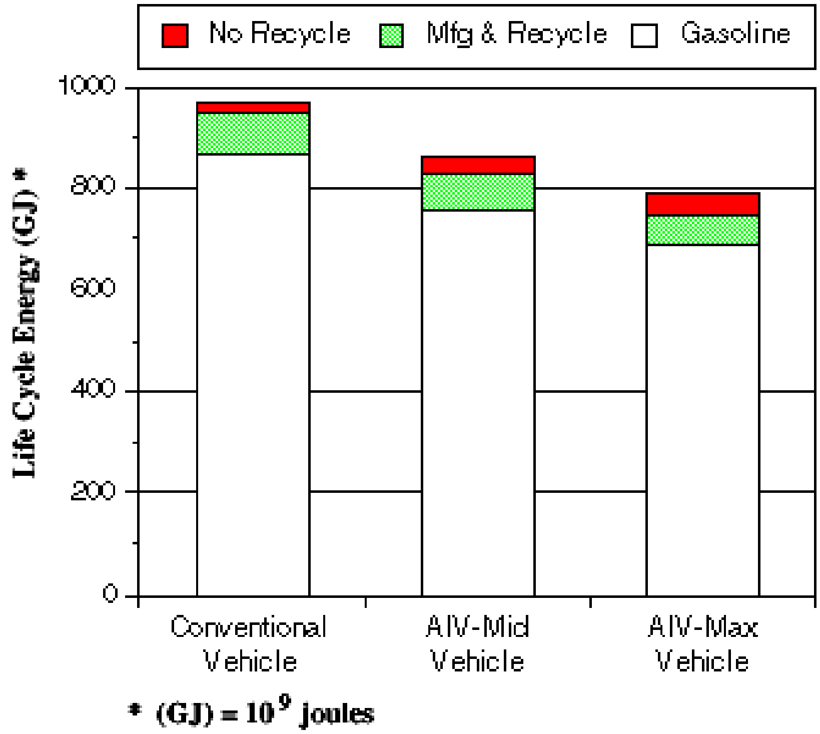

Figure 5. Life-Cycle Energy Consumption of Conventional and Aluminum-Intensive Mid-Size Passenger Cars

The AIV-Max vehicle, representing maximum aluminum substitution, contains a significant amount of cast aluminum as well as wrought aluminum. The embodied primary energy in the AIV-Max vehicle is 58 GJ, or about 12% less than the embodied primary energy in the AIV-Mid vehicle, and about 27% less than the embodied energy in the conventional vehicle. The embodied primary energy in the AIV-Max vehicle is lower than the embodied primary energy in the AIV-Mid vehicle mainly because cast aluminum replaces more energy-intensive steels and cast iron (on a weight basis). The embodied primary energy of the cast and wrought aluminum in the AIV-Max vehicle is 36 GJ, or 65% of the total embodied primary energy in the vehicle materials.

Compared to energy savings potential from weight reduction, recycling does not save much energy. Further, weight reduction affects petroleum usage 100%, while recycling has very little effect on petroleum usage. However, compared to the other materials, recycling aluminum back to wrought aluminum saves a significant amount of energy. Recycling wrought aluminum to cast aluminum does not save energy, because cast aluminum already contains recycled content and additional recycled aluminum will only add to the supply of cast-grade metal.

National Energy-Saving and Fuel-Use Impacts of Aluminum-Intensive Vehicles -- The energy saving for the entire U.S. vehicle fleet was estimated (Figure 6) assuming that vehicles with maximum aluminum substitution are introduced in quantity in the year 2005 and recycling rates shown in Table 7 (recycle scenario 1) are achieved. Total primary energy, including energy needed to extract, refine, and distribute the fuel, was considered. In 2010, national annual energy saving is predicted to be about 358 PJ (358 x 1015 J). National energy saving as a result of improved vehicle fuel economy alone amounts to almost 400 PJ, or a saving of 2.2% of total oil consumed by light-duty passenger cars and light trucks. Manufacturing energy increases in the early years of AIV commercialization because we assume new primary aluminum is required. Later, as AIVs are scrapped and wrought alloys are produced from scrap, a net energy saving over the manufacturing and recycling life-cycle results. In 2020, the total annual primary energy saving is predicted to amount to over 850 PJ (790 PJ from vehicles, or 4.1% of vehicle fleet fuel consumption) and 1,080 PJ in 2030 (950 PJ from vehicles, or 4.6% of vehicle fleet fuel consumption).

The fuel mix changes over time, as shown in Figure 7. Relative to the base case, AIV-Max commercialization in 2005 results in an immediate increase in the use of natural gas and nonfossil energy, and a decrease in coal. This occurs because primary aluminum production is more dependent on nonfossil energy (primarily hydroelectric power) than steel, which is more dependent on coal. Use of natural gas increases due to the large amount of aluminum castings being used by the AIV-Max. Aluminum castings are assumed to come primarily from recycled aluminum, which is refined in natural-gas-fired reverberatory furnaces. We assume aluminum is available in the quantity required for castings in the AIV-Max vehicles. Initially, the supply of wrought aluminum will be from new production requiring higher nonfossil energy. Later, as primary aluminum production decreases due to increased recycling of wrought aluminum to wrought aluminum, nonfossil energy use decreases, while coal continues to decrease as AIVs penetrate the market. In later years, natural gas use remains high because recycled aluminum is used. Relative oil consumption shown in Figure 7 includes oil used by manufacturing and recycling processes and by the vehicle. A slight increase (about 5%) in use of oil is predicted for manufacturing because more oil is used for aluminum production than for steel production Table 6). However, the additional amount of oil used in manufacturing is small compared to the oil saved as a result of the improvement in vehicle fuel economy. Overall, compared to the base case (conventional steel vehicles), national oil consumption is reduced by about 4.6% or 950 PJ by 2030, if AIV-Max vehicle technology is commercialized by 2005.

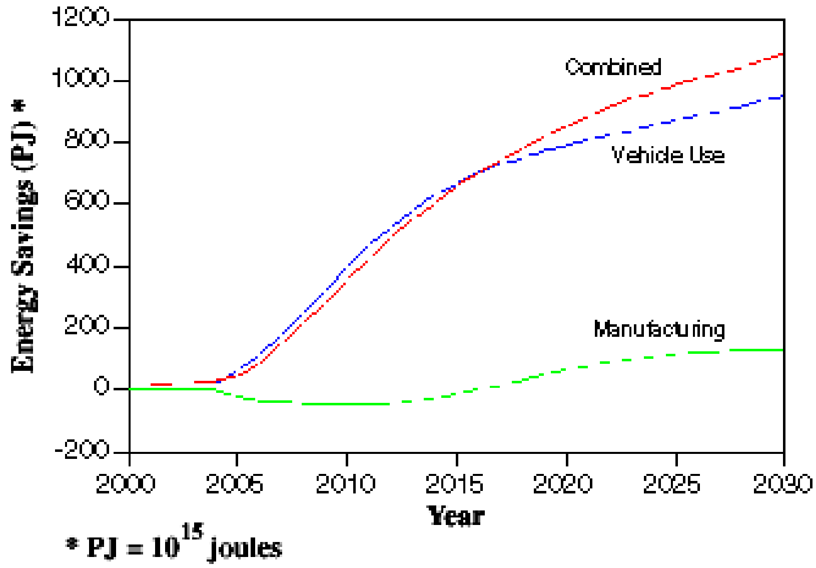

Figure 6. Vehicle Fleet Energy Savings Comparison, Reference Fuel Price Scenario

CONCLUSIONS

We have presented an analysis of the mass reduction potential of aluminum, as a substitute for steel, and the resulting cost increments and life-cycle energy implications for light-duty passenger vehicles in the United States. The vehicles showed significant market penetration potential even under the current and projected low, but slowly increasing, fuel prices. The following conclusions were reached:

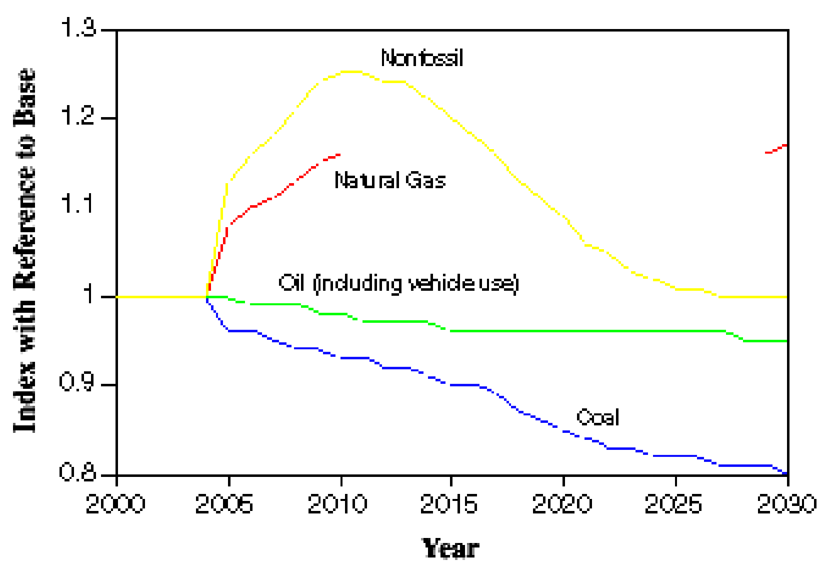

Figure 7. Changes in Fuels Used Over Time, Reference Fuel Price Scenario

- A 19-31% weight reduction (270-460 kg) is possible with the intensive use of aluminum in passenger cars and light trucks, resulting in a fuel economy improvement of 12.5-20% for AIVs over conventional steel vehicles.
- Regulatory actions (such as an increase in the CAFE standards) are not needed to lower vehicle-fleet energy consumption if improvements in aluminum manufacturing and assembly technology reduce the increase in per-kg price of AIVs to no more than

$2.95/kg weight saved. This situation holds true even if U.S. gasoline prices remain historically low and consumer preference for larger vehicles continues.

- If AIVs are commercialized on a mass scale by 2005, national petroleum energy saving of about 2.2% (400 PJ) is possible by 2010, 4.1% (790 PJ) by 2020, and 4.6% (1,080 PJ) by 2030.
- The primary energy embodied in the vehicle materials and manufacturing process is small relative to the fuel energy consumed by the vehicle. The primary energy embodied in the vehicle materials and manufacturing process ranges between 8% (with recycling) and 12% (without recycling) of the total primary energy consumed over the lifetime of the vehicle.
- Recycling does not significantly reduce vehicle life-cycle energy usage. (Environmental impacts of recycling were not evaluated.)
- Compared to recycling other widely used vehicle materials, recycling wrought aluminum back to wrought aluminum saves the most energy.
- Over the AIV life cycle, far more oil is saved than such other fuels as coal, natural gas, and nonfossil fuels.
- As AIVs penetrate the market, the fuel mix for vehicle materials and manufacturing changes. Over the short term, before AIVs are scrapped, use of nonfossil fuels (such as hydroelectric power and nuclear power), oil, and natural gas increase, while the use of coal decreases, compared to the period prior to introduction of AIVs. Over the long term, as AIVs are scrapped and recycled wrought aluminum enters the market, natural gas use remains higher, while nonfossil and oil use drops over time to levels that existed before AIVs were introduced. Coal use remains lower because less steel is used.
- Many of the results of this study are not necessarily applicable to vehicles built outside of the United States, but many others may be used with caution as general indicators.

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NOTES

[1] In this study, vehicle utility is assessed using the following measures: (1) passenger and cargo volume and (2)

vehicle acceleration. We assume vehicle acceleration performance is held constant, so for a lighter vehicle, the engine size is reduced accordingly.

[2] The authors conclude that the extensive use of high-modulus, carbon-fiber polymer-matrix composites for vehicle body and chassis is not economical, even assuming a significant decrease in materials cost as a result of mass production and assuming the costs of assembly and finishing are the same as for the conventional vehicle [2]. Therefore, the authors do not consider carbon-fiber polymer-matrix composites as a viable option during the next 25-35 years.

[3] The value of secondary weight savings per kilogram of primary weight savings cited by Ford [11] is based on a 1979 mid-size vehicle. Today's mid-size vehicle uses materials more efficiently (i.e., unitized body vs. separate frame). In our judgment, 0.75 kg of secondary weight savings per kilogram of primary weight savings is not possible in today's vehicle simply by redesigning current chassis components to account for the lighter load. We used a value of 0.5 for this assessment.

TABLES

Table 1. Estimated Average Material Content in U.S.-Built Passenger Cars (1994)

Material	Mass (kg)	%
Mild steel	631	43.8
High-strength steel	120	8.3
Stainless steel	20	1.4
Other steels	19	1.4
Total steel	790	54.9
Cast iron	185	12.8
Total ferrous	975	67.7
Plastics/composites	112	7.7
Aluminum	83	5.8
Rubber	61	4.2
Glass	40	2.7
Copper	19	1.3
Powder metal	12	0.8

Zinc die castings	7	0.5
Other materials	45	3.1
Fluids/lubricants	86	5.9
Total	1440	100

Table 2. Comparison of Steel and Aluminum Mercury Sable Body

		Steel Mass (kg)		Aluminum Mass (kg)		Saving	
Component	Number	Each	Total	Each	Total	kg	% Mass
Fenders	2	3.2	6.4	1.4	2.8	3.6	57
Decklid	1	17	17	5.4	5.4	6.6	55
Hood	1	22.2	22.2	9.1	9.1	13.2	59
Front Door	2	17	34	9.8	19.6	14.5	43
Rear Door	2	12.9	25.8	8.2	16.4	8.5	37
Unit Body	1	270.3	270.3	145	145	125.2	46
Total			371		198	173	47

Table 3. Aluminum-Intensive Vehicle Weight Scenarios

		AIV-Mid			AIV-Max		
Material	Baseline Weight(kg)	Primary Weight(kg)	Secondary Weight Savings(kg)	Net Weight(kg)	Primary Weight(kg)	Secondary Weight Savings(kg)	Net Weight(kg)
Steels	790	418	(54)	364	486	(33)	153
Cast iron	185	418	(25)	160	54	(10)	44
Wrought aluminum	17	215		215	215		215
Cast aluminum	66	66	(9)	57	252	(45)	207

Reinforced plastics	14	14		14	14		14
Unreinforced plastics	98	98		98	98		98
Other	271	271	(9)	262	271	(21)	250
Total	1441	1265	(95)	1170	1090	(109)	981
Weight reduction	--	176	95	271	351	109	460

Table 4. Production and Recycling Energy for Automotive Materials [19]

	Energy (MJ/kg)	
Material	Production	Recycle
Steel	65	52
Cast iron	r[a]	37
Wrought aluminum	231	52
Cast aluminum	r[a]	44
Reinforced plastic	56	37
Unreinforced plastic	79	14
Copper	140	35
Zinc	112	8
Powder metal	93	n/r[b]
Rubber	88	n/r[b]
Other	88	n/r[b]
Fluids	88	n/r[b]

[a] We assume these materials are produced from recycled scrap.
[b] We assume these materials are not recycled

Table 5. **Energy Purchased and Recycling of Automotive Materials and Automobiles** [19,20]				
	Energy Source (fraction)			
	Coal	Oil	Natural Gas	Electricity[a]
Material:				
Steel	0.66	0.03	0.22	0.09
Cast iron	1.00	--	--	--
Wrought aluminum[b]	0.04	0.12	0.34	0.50[c]
Cast aluminum	--	--	1.00	--
Plastics	0.14	0.21	0.55	0.10
Copper, zinc[b]	0.08	--	0.70	0.23
Glass	-- ;	0.03	0.78	0.19
Powder metal[e]	0.56	0.02	0.18	0.24
Rubber and other[d]	0.14	0.21	0.55	0.10
Process:				
Automobile assembly	--	--	--	1.00
Automobile shredding	--	--	--	1.00

[a] At 3,600 kJ/kWh.
[b] Values are for production from virgin resources; recycling primarily uses natural gas.
[c] 20% hydroelectric and 30% non-hydroelectric.
[d] No recycling.
[e]Assume energy for production from virgin resources is the same as for steel. No recycling.

Table 6. Fuels Used for Production and Recycling of Automotive Materials and Automobiles [19,20]				
	Fuel (fraction)			
Material	Coal	Oil	Natural Gas	Nonfossil
Steel[b]	0.72[a]	0.03	0.23	0.02
Cast iron	1.00	--	--	--

Wrought aluminum[c]	0.50	0.08	0.27	0.16
Cast aluminum	--	--	1.00	--
Plastics	0.18	0.20	0.60	0.02
Copper, zinc[c]	0.32	0.03	0.52	0.09
Glass[d]	0.25	0.05	0.62	0.09
Powder metal[e]	0.72	0.03	0.23	0.02
Rubber and other[d]	0.18	0.20	0.60	0.02
Process				
Automobile assembly[f]	0.69	0.04	0.04	0.23
Automobile shredding[g]	0.69	0.04	0.04	0.23

[a] Hydroelectric, nuclear and renewable (biomass) [b] Over 50% is from coal used to make coke for the blast furnace.
[c] Values are for production from virgin resources; recycling primarily uses natural gas.
[d] No recycling.
[e] Assume energy for production from virgin resources is the same as for steel. No recycling.
[f] Assembly fuel mix data from DeLuchi [20].
[g]Assume same fuel mix as automobile assembly.

Table 7. Recycling Rates Assumed for Scenario 1

	Percent Recycled	
Material	Year 2005	Year 2030
Steel	87	90
Cast iron	87	90
Wrought aluminum	93	93
Cast aluminum	90	90
Reinforced plastic	8	15

Unreinforced plastic	20	35
Copper	76	85
Zinc	5	30
Powder metal	0	0
Rubber	0	0
Other	0	0
Fluids	0	0

Table 8. Net End-Use Energy Available from Fuels

	Coal	Fuel Oil	Natural Gas	Reformulated Gasoline
Energy fraction	0.98	0.90	0.88	0.81

Source: DeLuchi [20]. We divided the above fractions by the energy values listed in Table 4 to estimate primary energy, which includes extraction, refining, and distributing the fuel.