Life Cycle Economic and Environmental Implications of Using Nanocomposites in Automobiles

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By reducing the energy and materials required to provide goods and services, nanotechnology has the potential to provide more appealing products while improving environmental performance and sustainability. Whether and how soon this potential could be realized depends on phrasing the right research and development (R&D) questions and pursuing commercialization intelligently. A sufficiently broad perspective at the outset is required to understand economic and technical feasibility, estimate life cycle environmental implications, and minimize unanticipated negative impacts. The rapid rise in federally funded nanotechnology R&D dictates that consideration of societal benefits will have a large role in setting the R&D agenda. We estimate potential selected economic and environmental impacts associated with the use of nanotechnology in the automotive industry. In particular, we project the material processing and fuel economy benefits associated with using a clay−polypropylene nanocomposite instead of steel or aluminum in light-duty vehicle body panels. Although the manufacturing cost is currently higher, a life cycle analysis shows potential benefits in reducing energy use and environment discharges by using a nanocomposite design.

Introduction

Federal investment in nanoscale science, engineering, and technology has increased from $270 million in 2000 to $710 million requested for 2003. Policy-makers need to understand the potential economic and environmental implications of a nanotechnology innovation to make informed judgments concerning research and development (R&D). Unfortunately, few detailed analyses exist of the specific implications of nanotechnology for a given product, process, or market. Here, we compare selected economic and environmental implications of replacing steel with nanocomposites or aluminum in light-duty vehicle body panels.

Markets for vehicle safety, performance, and fuel efficiency provide a demand for new and advanced materials in automotive applications. The National Institute of Standards and Technology (NIST) has sponsored a $15.8 million ($7.8 million from federal funding) Advanced Technology Program (ATP) with Dow Chemical to produce low-cost, high-strength nanocomposites for automotive parts (*1*). Weight reduction is an important issue for motor vehicles since reducing weight is the principal way to increase fuel economy (*2*, *3*). For example, substituting aluminum for steel in body components has received substantial analysis (*4*). General Motors Corp. began using a thermoplastic olefin (TPO) nanocomposite in an optional step-assist for the Chevrolet Astro and the GMC Safari mini-vans. Substituting reinforced polymers in vehicle body components is a promising approach to weight reduction, but it is important not to compromise safety, cost, or other desired attributes. The competitiveness of the motor vehicle market together with production of 17 million vehicles per year means that materials must offer superior cost and performance to win a place on vehicles. However, if materials alternatives are competitive and successfully used, the potential social savings are large.

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Materials

Nanoclay-Reinforced Polymer Composites. Platelets with dimensions in the micron range are used at loading levels between 15 and 60% to enhance the mechanical properties of polymeric materials. Unfortunately, such high loading levels often harm other mechanical, thermal, optical, and/or rheological properties. The mechanical properties of a platelet-reinforced polymer are primarily determined by the properties of the reinforcing platelets, the properties of the polymer matrix, the nature and strength of the interfacial bond between the reinforcing platelets and matrix, and the surface area of the interfacial bond. The area of the interfacial bond in a polymer composite is determined by the aspect ratio (diameter/thickness) of the platelets and the platelet loading level. As platelet thickness decreases, aspect ratio and the affect of the platelet on the polymer's mechanical properties increase. Platelets with thickness dimensions in the nanometer range are expected to achieve mechanical enhancements at lower loading levels without compromising other material properties (*5*−*8*).

Montmorillonite clays are generally ion-exchanged to improve their compatibility and dispersability in a polymer matrix. An individual platelet of montmorillonite clay is illustrated in Figure 1. Stacks of this organoclay, with thickness dimensions in the micron range, have been used as conventional polymer reinforcement for several decades. Treated montmorillonite organoclay that is dispersed in a polymer in individual or small stacks of platelets is commonly called nanoclay. Two critical challenges confront processing nanoclay and the subsequent nanocomposite: exfoliation and dispersion. The exfoliation of montmorillonite into individual platelets and homogeneous dispersion of uniformly oriented nanoclay into the polymer matrix, shown in Figure 2, will improve a composite's mechanical properties.

Commercializing a reinforced polymeric composite requires achieving the desired performance at low cost. The 2002 market price for polypropylene filled 2% by volume (10% by weight) with montmorillonite nanoclay is $1.25/lb, as summarized in Table 1. Current R&D at Argonne National Laboratory aimed at integrating surface modification in the clay recovery and purification processes to create self-activated clays that will be dispersible without the use of compatibilizing agents could reduce the nanocomposite material cost to approximately $1.00/lb (*10*). Other potential applications for nanoclay-based composites include underground piping using nanoclay to prevent the herbicide from leaching out to offer protection from roots, beer bottles with nanoclay to improve the oxygen barrier, electrical closures with nanoclay to provide the required flame-retardant properties, and other packaging applications (*11*, *12*).

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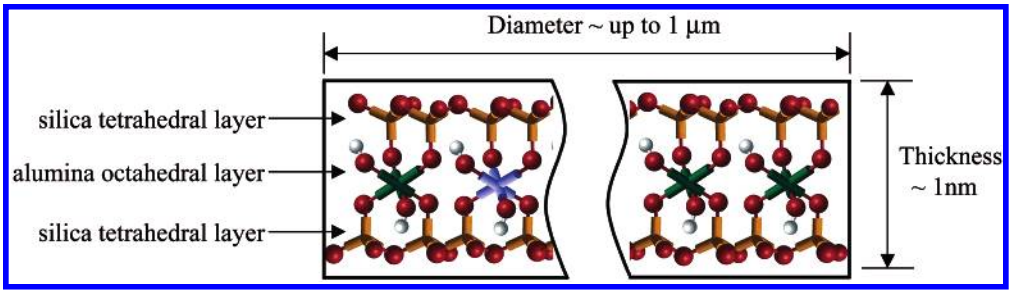

FIGURE 1. Side view of one sheet of montmorillonite clay (*9*). Modified from the original source.

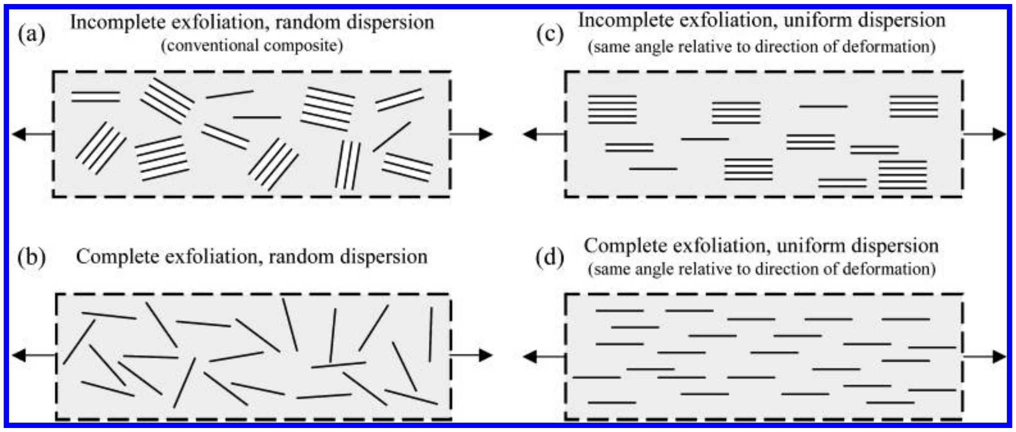

FIGURE 2. Illustrations of exfoliation and platelet orientation.

TABLE 1. Costs for Polypropylene Nanocomposite with 2 vol % Nanoclay

constituent	wt %	cost/lb
polypropylene and elastomer for TPO	70−75	\$0.65−1.00
compatibilizer (i.e., maleated polypropylene)	15−20	\$1.50
fully treated nanoclay	10	\$2.00−4.00
cost of montmorillonite clay−polypropylene nanocomposite		~\$1.25

TABLE 2. Projected Values of Variables Used To Predict Young's Modulus

variable	description	lower bound	upper bound
E_{matrix}	Young's modulus of polypropylene matrix	1.1 GPa (*18*)	1.55 GPa (*18*)
E_r	ratio of platelet to matrix modulus	100 (*16*)	100 (*16*)
A_f	aspect ratio of platelet (diameter/thickness)	100 (*16*)	1000 (*16*)
ϕ	volume ratio of platelets in matrix	1% (*16*)	6% (*16*)
N	number of platelets per stack	5 (*16*)	1 (*16*)
S	inter-platelet spacing	0.3 nm(*19*)	7 nm (*20*)
T	thickness of the platelet	0.95 nm (*21*)	1 nm (*19*)
Young's modulus of the clay−polypropylene composite		1.4 GPa	10.3 GPa

Methods

Estimating Weight Reduction Using Young's Modulus. A complete calculation of the potential weight reduction requires a component-by-component analysis that minimizes weight given the functional requirements, geometry, and material properties of each component. Before making such a large investment, a company would want a preliminary analysis indicating that the potential benefits from material substitution merit the time and expense.

The need for a stiff body drives automotive body panel design (*13*, *14*). Ashby (*15*) developed the material index $M = E^{1/3}/\rho$, where ρ is the density and E is the Young's modulus of a material, for evaluating the weight of panels made from different materials with equal stiffness. The following assumptions allow us to approximate the potential weight reduction at equal stiffness: (i) functional, geometric, and material properties are separable; (ii) performance as defined by nonstiffness requirements will be maintained in all components; and (iii) only the material thickness will be varied.

Brune and Bicerano (*16*) developed an idealized model based on micromechanical principles to estimate Young's modulus for a nanocomposite on the basis of incomplete exfoliation and with all platelets aligned with the direction of deformation, as shown in Figure 2c. Because of the lack of experimental data, there is substantial uncertainty associated with the variables used in the Brune−Bicerano model. We gleaned lower and upper estimates for each variable, shown in Table 2, from the literature and discussions with experts. From these values, we estimated lower and upper bounds of 1.4 and 10.3 GPa for Young's modulus of a nanoclay−polypropylene composite.

Current experimental methods have arrived at Young's modulus values higher than 2 GPa (*7*, *17*). An upper bound

TABLE 3. Projected Percentage Primary Weight Reduction

material	density, ρ (g/cm^3)	Young's modulus, E (GPa)	material index, $M = E^{1/3}/\rho$	primary wt reduction (%)	thickness ratio
steel	7.8	210	0.8		1.0
aluminum	2.7	71	1.5	50	1.4
nanocomposite, lower	0.92	1.4	1.2	38	5.3
nanocomposite, upper	0.95	10.3	2.3	67	2.7

of 10.3 GPa is too optimistic because it assumes uniform platelet orientation in the direction of deformation and consequently a much lower modulus in the transverse direction. Multidirectional stiffness is needed for automotive applications, with a certain level of stiffness required for vertical body panels and additional stiffness required for horizontal body panels. A nanocomposite characterized by the lower bound may not meet the level of performance required for body panel applications. We use the lower and upper theoretical bounds throughout our analysis to show an inclusive range of possible performance. A more realistic range is 3−7 GPa, which would tighten the results found in this study.

Using Ashby's material index, we estimate a theoretically obtainable primary weight reduction of 50% from aluminum substitution and 38−67% (for E = 1.4−10.3 GPa) from nanocomposite substitution, shown in Table 3. A range of 3−7 GPa for the nanocomposite Young's modulus would result in a 51−62% weight savings. The estimates in Table 3 have the following uncertainties:

(i) The Brune−Bicerano model has not been verified experimentally and assumes perfect adhesion (and therefore perfect load transfer) between the clay platelets and the matrix.

(ii) Designing parts according to an alternative material's mechanical properties may generate additional weight reduction. In this analysis, we assumed that material alternatives are substituted panel-for-panel in a conventional unibody design. Other design types may more effectively utilize the properties of nanocomposites in panel applications. For example, the 2002 Saturn VUE sports utility vehicle utilizes a steel space frame design with polymer panels.

(iii) Maintaining the stiffness of a body panel using a material with a significantly lower Young's modulus requires a sizable increase in part thickness, as shown by the thickness ratio in Table 3. Such a large increase in a component's cross-section area or thickness may violate design constraints.

(iv) A component may be over- or under-designed when stiffness is not the limiting property. Other requirements that must be evaluated include energy absorption, dent resistances, durability, cost, fabrication, appearance, availability of materials, acoustical/vibrational comfort, dimensional constraints/stability/consistency, and overall vehicle performance. Each of these design requirements would need to be evaluated in more detail to assess the feasibility of using nanocomposites in automotive applications.

(v) The approximations used here may be more accurate for aluminum than for composites because the properties of steel and aluminum are more similar.

Improved Fuel Economy. Experts project an additional secondary weight savings of up to 1 lb for every pound of primary weight savings (*3*, *22*, *23*). We assume that an additional 0.5-lb secondary weight reduction per pound of primary weight savings can be achieved. This secondary reduction includes downsizing the chassis and powertrain to match initial power performance. We assume that all of the total (primary and secondary) weight reduction will be converted to improved fuel economy. However, in the current market, there are many different drivers for material selection and weight reduction. Several commercialized motor vehicle bodies have been manufactured from aluminum, such as the Honda Insight, Honda NSX, Audi A2, Audi A8, and Chrysler Prowler. Only in the Insight does the fuel economy appear to be a key driver in material selection.

Using fuel economy and curb weight data for existing automobiles grouped by 0−60 mph acceleration, we evaluated the predictive ability of three equations for converting large weight reductions to improved fuel economy: a sedan equivalent estimation (*24*), a 10% weight reduction results in a 7% improvement in fuel economy (*25*), and a Euromix 100-kg reduction results in a 0.3−0.4 L/100 km reduction in fuel consumption (*26*). All equations tend to underestimate improvements in fuel economy. We use the sedan equivalent equation, shown in eq 1, because it gave the best predictions:

$$\mathrm{mpg}_2 = \mathrm{mpg}_1\left(\frac{W_1}{W_2}\right)^{0.72} \qquad (1)$$

where mpg_i is the fuel economy in mi/gal for vehicle i and W_i is the weight of vehicle i.

We use several approximations to provide results that include all passenger cars and light trucks. The fleet average curb weight and fuel economy for model year 2000 passenger cars and light trucks were used as the baseline. Body panels of the baseline car and truck are assumed to consist entirely of the mildest grades of sheet steel used in automobile manufacturing. We estimated that body panels make up 11% of total vehicle weight on the basis of the following two assumptions: the 1997 Ford Taurus GL Sedan, in which body closures account for 7% and the body-in-white (BIW) accounts for 19% of the total weight, was assumed to be representative of all vehicles; and we estimated that panels make up 100% of the body closures and 20% of the BIW components.

All calculations were made based on 16.9 million light-duty vehicles produced each year, 210 million vehicles on the road, a 45% light truck market share, and a 150 000-mi, 10-yr vehicle life. The costs in 2002 U.S, dollars include \$0.90/gal manufacturing cost for gasoline, \$1.50/gal consumer price for gasoline, \$0.33/lb for sheet steel, \$0.05/lb for steel production scrap, \$1.15/lb for aluminum, \$0.60/lb for aluminum production scrap, and \$1.25/lb for the nanocomposite. We assumed that processing body panels from all three materials would result in 50% production scrap. The 50% steel and aluminum production scrap will be sold and recycled. The 50% nanocomposite production scrap will be fed into an auto-grinder and reused in the forming processes.

Results

Projected Fuel Savings and CO_2 Reduction. A comparison of the projected annual fuel savings and CO_2 reduction from vehicle use, assuming that all 210 million light-duty vehicle bodies on the road in the United States are made with aluminum or the nanocomposite is presented in Table 4. Estimated annual CO_2 reductions from vehicle use are 65 million t from aluminum substitution and 49−87 million t from nanocomposite substitution.

TABLE 4. Projected Fuel Savings and CO_2 Reduction per Vehicle and for All Vehicles on the Road in the United States (210 Million Vehicles)

	per vehicle				for all 210 million vehicles on the road	
vehicle type	wt of body panels per vehicle (lb)	primary wt reduction (lb)	secondary wt reduction (lb)	adjusted wt, W_2 (lb)	annual gasoline savings (billion gal)	annual reduction in CO_2 emissions (million t)
Steel						
passenger car	338	0	0	3126	0.0	0
light truck	455	0	0	4210	0.0	0
total					0.0	0
Aluminum						
passenger car	168	170	85	2871	3.6	31
light truck	226	229	114	3867	4.0	34
total					7.6	65
Nanocomposite, Lower Bound Performance						
passenger car	210	128	64	2935	2.7	23
light truck	283	172	86	3952	3.0	26
total					5.7	49
Nanocomposite, Upper Bound Performance						
passenger car	113	225	113	2788	4.8	41
light truck	153	303	152	3755	5.3	46
total					10.1	87

TABLE 5. Change in Life Cycle Environmental Impact from Substituting Nanocomposites or Aluminum for Steel in Body Panels for One Year's Fleet of Vehicles in the United States (16.9 Million Vehicles)[a]

		nanocomposite	
effects	aluminum	lower	upper
electricity used (M kw-h)	48 000	−4 000	−9 200
energy used (TJ)	−51 000	−100 000	−240 000
conventional pollutants released (t)	320 000	−170 000	−300 000
OSHA safety (fatalities)	−4	−3	−7
greenhouse gases released (t of CO_2 equiv)	−3 800 000	−7 200 000	−16 000 000
fuels used (t)	−100 000	−99 000	−230 000
ores used, at least (t)	−5 300 000	−4 900 000	−6 300 000
hazardous waste generated (RCRA, t)	−1 900 000	360 000	−1 800 000
toxic releases and transfers (t)	−13 000	−110	−14 000
weighted toxic releases and transfers (t)	−56 000	−68 000	−88 000
water used (billion gal)	−150	−120	−200

[a] See www.eiolca.net for explanations of the valuation and weighting.

Economic Input−Output Life Cycle Assessment. Analysis of CO_2 reduction during vehicle use gives only a partial picture of the environmental impacts associated with material substitution in vehicle components. The industrial ecology of nanotechnology must include an analysis of the environmental impact associated with the full life cycle of the commercialized product or process. This includes extraction of raw materials, production, use, and end of life. The Economic Input−Output Life Cycle Assessment (EIO−LCA) model developed at Carnegie Mellon (http://www.eiolca.net/) calculates the economic and environmental effects from production and across the entire supply chain for purchases in any of 485 commodity sectors in the U.S. economy (*27, 28*). In particular, for purchases of a nanocomposite to replace steel in the vehicle model, the model calculates the direct and life cycle implications for cost, materials and fuels inputs, emissions of conventional pollutants and greenhouse gases, toxic releases, and RCRA hazardous waste.

The sectors used in this analysis include "petroleum refining", "blast furnaces and steel mills", "primary aluminum", and "plastics materials and resins". We input the change in economic activity for each sector into the 1992 EIO−LCA model and used eq 2 to total the environmental impacts. Table 5 summarizes the change in each environmental impact from producing material for body panels and the reduced lifetime fuel requirement for one year's fleet of vehicles. A negative result indicates a reduced environmental impact. Figure 3 illustrates the relative percentage change for each environmental impact:

$$\begin{aligned}
&\text{impact change} = \\
&\quad (\text{effect from producing alternative material for body panels}) \\
&+ (\text{effect from producing lifetime petroleum}) \\
&- (\text{effect from producing steel eliminated due to secondary wt savings}) \\
&- (\text{effect from producing steel for body panels for baseline vehicles}) \\
&- (\text{effect from producing lifetime petroleum for baseline vehicles})
\end{aligned} \quad (2)$$

For example, the lower level of manufacturing and fuel production associated with either an aluminum or a nanocomposite material substitution would result in an energy savings of 51−240 thousand TJ, a savings of 5−6 million t of ore, and 3−7 fewer occupational fatalities. Environmental impact would be expected to increase in a few instances, such as electricity use and conventional pollutants from an aluminum substitution and hazardous waste generation from a nanocomposite lower-bound substitution. Overall, the life cycle environmental impact of automobiles would be reduced from a material substitution in motor vehicle body panels. Although these savings are small relative to the totals for motor vehicles, they are substantial. If the costs of nanocomposites can become competitive with steel, a substitution would be a win−win situation where costs can be reduced, fuel saved, emissions of pollutants and greenhouse gases lowered, and total hazardous waste reduced by substituting a nanocomposite for steel in the vehicle body.

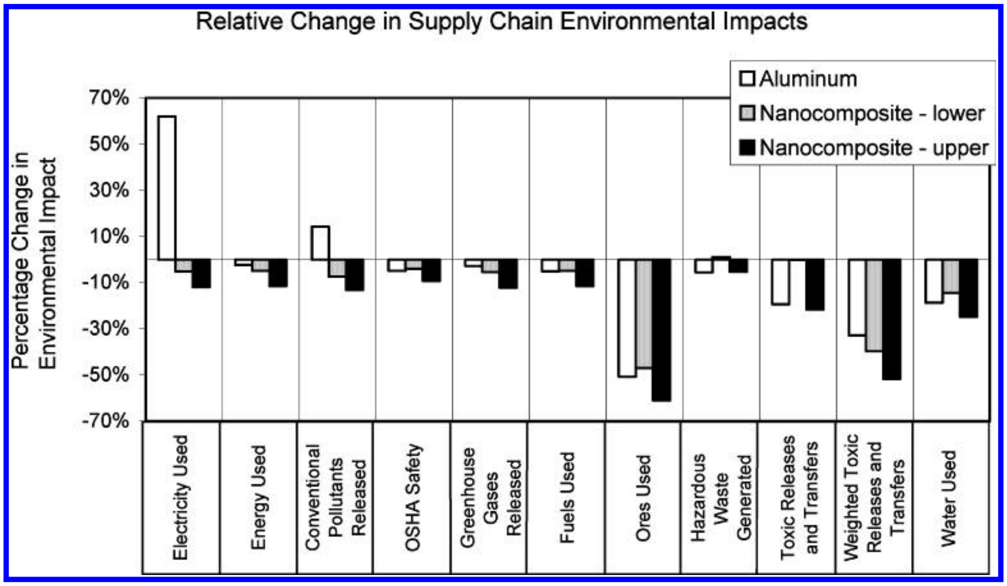

FIGURE 3. Relative change in life cycle environmental impact from substituting nanocomposites or aluminum for steel in body panels for one year's fleet of vehicles in the United States (16.9 million vehicles).

There are several important limitations associated with using the EIO−LCA model for estimating the environmental effects across the supply chain in this study:

(i) The model does not distinguish between recycled and virgin material. If recycled steel or aluminum can be used, energy use and pollutant discharges would be reduced. For example, the energy required to produce recycled aluminum is estimated to be approximately 1/20th of the energy required for the production of virgin aluminum (*29*).

(ii) The model does not distinguish between different costs or grades of materials. For example, the economic and environmental implications associated with a $1 million change in polypropylene production may be substantially different than an equal economic change in nylon production. However, both are included in the same sector.

(iii) The model assumes a linear relationship between economic input and environmental effect and does not consider fleet effects. For example, a large proportion of the electricity used in producing aluminum is from hydropower generation. It has been predicted that a substantial proportion of the additional electricity that would be required from a substitution of aluminum for steel in motor vehicle bodies for the entire fleet would be from coal-based generation. Considering fleet effects, such as energy mix, may dramatically change the relationship between economic input and environmental impact (*29*−*31*).

Global Warming Potential. The EIO−LCA model estimates the releases of four greenhouse gases (CO_2, CH_4, N_2O, and CFCs) and converts them into equivalent releases of CO_2. Figure 4 summarizes the CO_2 equivalents generated across the supply chain during material and lifetime petroleum production and the CO_2 emissions generated during vehicle use for the lifetime of a 1-yr fleet of vehicles (16.9 million vehicles). More than 93% of the CO_2 equivalents from material and petroleum production are from the release of CO_2 (rather than other greenhouse gases). The production of CO_2 equivalents associated with material production is 76 (alum) to 380 (nano, upper) times smaller than that of petroleum production and vehicle use—both related to fuel economy. Each material substitutions scenario results in a lower global warming potential primarily because of reduced fuel production and combustion. The largest reduction in global warming potential is expected from the substitution of the upper-bound nanocomposite for steel in motor vehicle bodies. The following reductions in CO_2 equivalents are

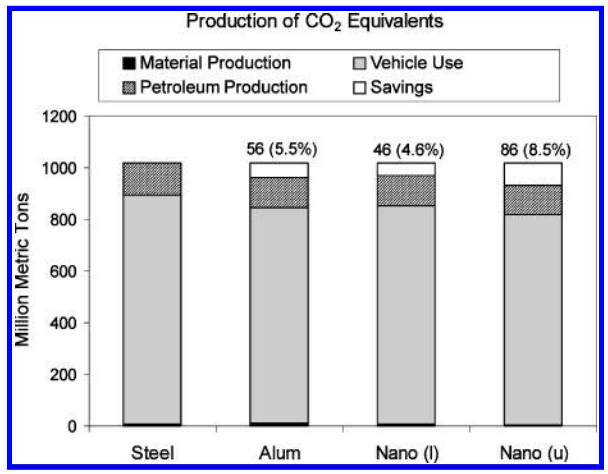

FIGURE 4. Life cycle production of CO_2 equivalents for one year's fleet of vehicles in the United States (16.9 million vehicles).

expected in this scenario: 6 million t from material production, 10 million t from lifetime petroleum production, and 70 million t from lifetime vehicle use—a total reduction of 86 million t or 8.5%. However, the global warming potential from substituting the lower-bound nanocomposite for steel is slightly higher than from aluminum substitution. Table 6 summarizes the 10 sectors contributing the highest global warming potential (not including vehicle use) for each material scenario. The petroleum refining sector is the highest contributor to global warming for all material scenarios, is associated with petroleum production, and generates roughly 50% of the CO_2 equivalents associated with material production for vehicle body panels and lifetime petroleum production.

Toxic Releases. EIO−LCA reports toxic releases and transfers both as total toxic releases and transfers and using sulfuric acid (H_2SO_4) as the reference chemical for weighted toxic releases and transfers. Figure 5 summarizes the total and weighted toxic releases and transfers during material and lifetime petroleum production for a 1-yr fleet of vehicles (16.9 million vehicles). For the nanocomposite lower bound, the expected total toxic releases and transfers are roughly the same as those from using steel and higher than those from using aluminum. However, the weighted toxic releases and transfers are lower than both steel and aluminum. For

TABLE 6. Ten Sectors Contributing the Highest Global Warming Potential (t of CO_2 equiv) for Each Material Scenario

steel		aluminum		nano, lower		nano, upper	
petroleum refining	50.9%	petroleum refining	49.3%	petroleum refining	51.5%	petroleum refining	53.4%
industrial inorganic and organic chemicals	24.5%	electric services (utilities)	30.2%	electric services (utilities)	24.8%	electric services (utilities)	24.6%
blast furnaces and steel mills	6.4%	crude petroleum and natural gas	6.2%	crude petroleum and natural gas	6.5%	crude petroleum and natural gas	6.7%
primary nonferrous metals, nec	5.3%	natural gas transportation	2.3%	industrial inorganic and organic chemicals	3.3%	industrial inorganic and organic chemicals	2.7%
electrometallurgical products, except steel	2.4%	industrial inorganic and organic chemicals	1.9%	natural gas transportation	2.5%	natural gas transportation	2.5%
nitrogenous and phosphatic fertilizers	1.8%	trucking and courier services, except air	1.5%	plastics materials and resins	1.8%	trucking and courier services, except air	1.3%
products of petroleum and coal, nec	1.3%	water transportation	1.2%	trucking and courier services, except air	1.3%	water transportation	1.2%
cement, hydraulic	1.2%	primary aluminum	0.7%	water transportation	1.2%	plastics materials and resins	1.1%
pulp mills	0.7%	wholesale trade	0.7%	blast furnaces and steel mills	0.8%	wholesale trade	0.7%
paper and paperboard mills	0.7%	blast furnaces and steel mills	0.7%	wholesale trade	0.7%	natural gas distribution	0.7%
total (top 10)	95.1%	total (top 10)	94.7%	total (top 10)	94.4%	total (top 10)	94.9%

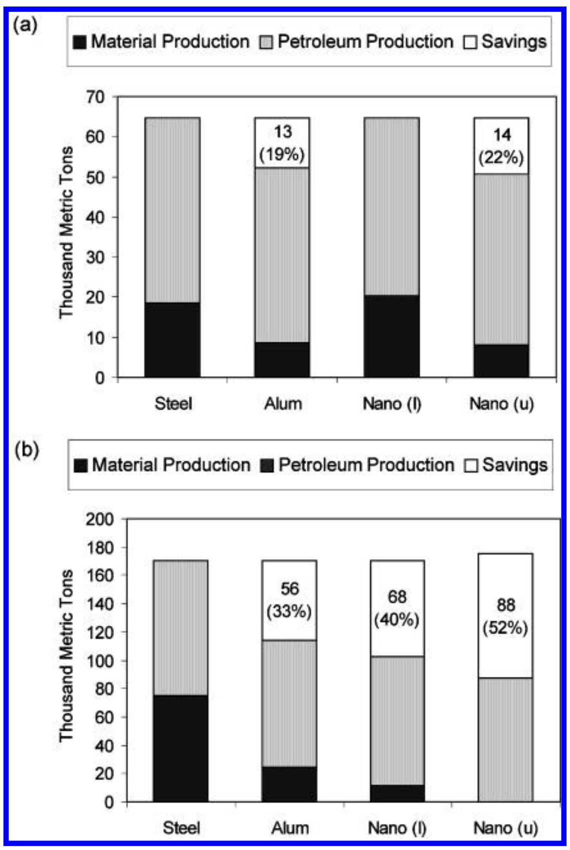

FIGURE 5. (a) Total and (b) weighted life cycle toxic releases and transfers for one year's fleet of vehicles in the United States (16.9 million autos).

the nanocomposite upper bound, both the total and weighted toxic releases and transfers are expected to be lower than those from using steel or aluminum. Tables 7 and 8 summarize the 10 sectors contributing the highest total and weighted toxic releases and transfers for each material scenario. The weighted toxic releases for steel are higher than those for the other materials primarily because releases from the "blast furnaces and steel mills" sector are more toxic than those from the "primary aluminum" or "plastics materials and resins" sectors.

The total and weighted toxic releases to each medium (air, water, land, and underground) are summarized in Figure

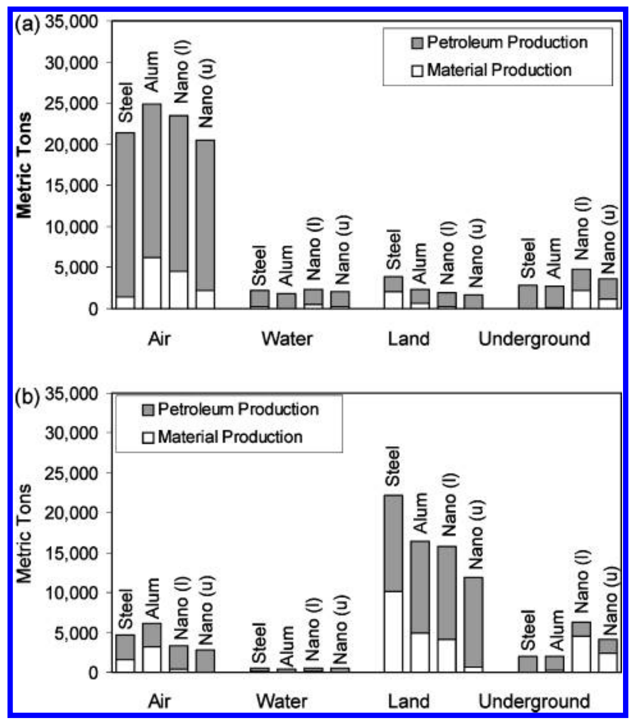

FIGURE 6. (a) Total and (b) weighted toxic releases to each medium for one year's fleet of vehicles in the United States (16.9 million vehicles).

6. The total releases to air are substantially higher than to all other media; however, the weighted toxic releases are substantially higher to land than all other media for all material scenarios. Material selection and reduced petroleum production cause the levels of toxics released to each medium to change; however, they do not cause any major shifts from one medium to another. The largest shift is in weighted toxic releases from land to underground when substituting nanocomposites for steel.

Cost Implications. Kelkar et al. (*4*) used technical cost modeling to compare the fabrication and assembly costs associated with steel and aluminum BIW designs. The estimated costs for a steel BIW for a midsize car at high production levels are shown in Table 9. These costs include the fixed and variable costs associated with materials, processing, and production. Little information is available

TABLE 7. Ten Sectors Contributing the Highest Total Toxic Releases and Transfers for Each Material Scenario

steel		aluminum		nano, lower		nano, upper	
petroleum refining	39.0%	petroleum refining	45.5%	petroleum refining	37.4%	petroleum refining	45.9%
blast furnaces and steel mills	31.7%	industrial inorganic and organic chemicals	15.8%	plastics materials and resins	22.6%	industrial inorganic and organic chemicals	21.4%
industrial inorganic and organic chemicals	12.6%	primary aluminum	13.2%	industrial inorganic and organic chemicals	22.1%	plastics materials and resins	15.7%
primary nonferrous metals, nec	4.4%	primary nonferrous metals, nec	7.1%	blast furnaces and steel mills	4.8%	blast furnaces and steel mills	2.6%
electrometallurgical products, except steel	1.1%	blast furnaces and steel mills	4.8%	primary nonferrous metals, nec	1.8%	primary nonferrous metals, nec	1.9%
pipe, valves, and pipe fittings	0.7%	nitrogenous and phosphatic fertilizers	0.8%	nitrogenous and phosphatic fertilizers	1.0%	nitrogenous and phosphatic fertilizers	1.0%
nitrogenous and phosphatic fertilizers	0.6%	pipe, valves, and pipe fittings	0.8%	pipe, valves, and pipe fittings	0.7%	pipe, valves, and pipe fittings	0.8%
storage batteries	0.5%	products of petroleum and coal, nec	0.7%	pulp mills	0.6%	storage batteries	0.6%
plastics materials and resins	0.5%	plastics materials and resins	0.7%	miscellaneous plastics products, nec	0.5%	chemicals and chemical preparations, nec	0.6%
chemicals and chemical preparations, nec	0.5%	storage batteries	0.7%	storage batteries	0.5%	pulp mills	0.6%
total (top 10)	91.6%	total (top 10)	90.1%	total (top 10)	92.0%	total (top 10)	91.0%

TABLE 8. Ten Sectors Contributing the Highest Weighted Toxic Releases and Transfers for Each Material Scenario

steel		aluminum		nano, lower		nano, upper	
blast furnaces and steel mills	45.7%	primary nonferrous metals, nec	19.1%	industrial inorganic and organic chemicals	20.0%	industrial inorganic and organic chemicals	18.9%
primary nonferrous metals, nec	9.8%	petroleum refining	11.6%	petroleum refining	13.2%	petroleum refining	15.8%
petroleum refining	8.3%	primary aluminum	10.7%	blast furnaces and steel mills	11.3%	storage batteries	8.0%
industrial inorganic and organic chemicals	6.9%	industrial inorganic and organic chemicals	10.4%	storage batteries	6.9%	primary nonferrous metals, nec	6.8%
storage batteries	4.2%	blast furnaces and steel mills	8.3%	primary nonferrous metals, nec	6.8%	pipe, valves, and pipe fittings	6.7%
pipe, valves, and pipe fittings	3.5%	storage batteries	6.1%	plastics materials and resins	6.7%	blast furnaces and steel mills	6.1%
primary smelting and refining of copper	3.3%	primary smelting and refining of copper	5.9%	pipe, valves, and pipe fittings	5.8%	nonferrous wiredrawing and insulating	5.9%
nonferrous wiredrawing and insulating	3.2%	pipe, valves, and pipe fittings	4.9%	nonferrous wiredrawing and insulating	5.1%	primary smelting and refining of copper	5.3%
electrometallurgical products, except steel	2.1%	nonferrous wiredrawing and insulating	4.6%	primary smelting and refining of copper	4.7%	plastics materials and resins	4.5%
fabricated metal products, nec	1.5%	rolling, drawing, and extruding of copper	2.2%	rolling, drawing, and extruding of copper	2.2%	rolling, drawing, and extruding of copper	2.5%
total (top 10)	88.4%	total (top 10)	83.8%	total (top 10)	82.5%	total (top 10)	80.6%

TABLE 9. Estimated Cost per Pound for Producing Motor Vehicle Bodies

BIW material	BIW weight		fabrication cost		assembly cost		total cost	
	(kg)	(lb)	($)	($/lb)	($)	($/lb)	($)	($/lb)
steel	215	474	800	1.70	250	$0.50	1050	2.20

about the costs for producing polymer vehicle bodies, especially at high production levels. This particular nanocomposite is currently processed on existing extrusion and injection molding equipment with only slight modifications to conventional polypropylene processing practices. Composite processing is slow and currently is not economically feasible in body components at high production levels. However, part consolidation offers a cost advantage in assembly.

Not knowing the costs of producing a body with a nanocomposite, we estimated the required cost per pound that would allow a nanocomposite to become economically competitive with steel. Here, required cost is the maximum allowable cost per pound for a nanocomposite with a given performance before it exceeds the cost savings due to reduced material weight and fuel consumption. Up to this point in the analysis, we estimated the environmental implications associated with a complete material substitution in 100% of the body panels for an entire fleet of vehicles or for all vehicles on the road. This effectively provides bounding estimates of the potential environmental performance. However, an incremental material substitution is more realistic. Equation 3 was used to estimate the required cost per pound based on the percentage of body panels in which steel is replaced by the nanocomposite and on the percentage primary weight reduction realized in these panel components via this substitution. We assumed that the costs shown in Table 9 are representative of the costs associated with producing body panels for all motor vehicles and of the savings per pound secondary weight reduction because of decreased materials, processing, and production. We also assumed that consumers consider the fuel associated with 3 yr of vehicle use in their purchasing decision (*2*). A 10% discount rate was assigned for the cost of gasoline over these 3 yr. This analysis does not consider the large costs associated with the R&D

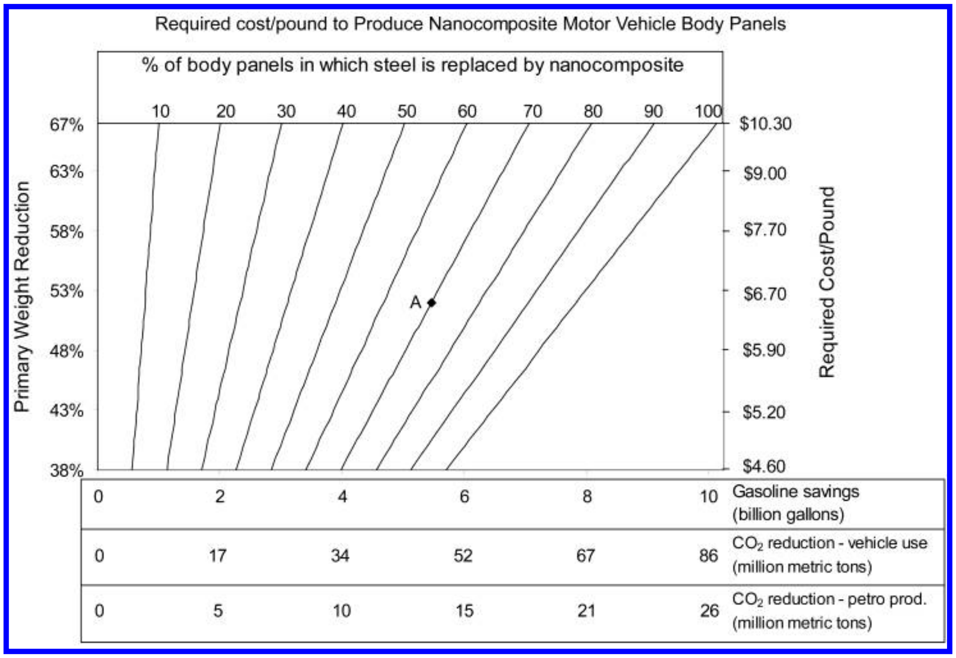

FIGURE 7. Required cost/pound for wide-scale commercialization of nanocomposite motor vehicle body panels (includes materials, processing, and production costs).

or start-up costs associated with this level of vehicle redesign. Nor does it consider the impact of scale effects on the cost of parts fabrication:

$$\text{required cost} = \frac{\begin{pmatrix}\text{wt of}\\ \text{steel}\\ \text{body}\\ \text{panels}\end{pmatrix}(\$2.20/\text{lb}) + \begin{pmatrix}\text{wt of}\\ \text{secondary}\\ \text{reduction}\end{pmatrix}(\$2.20/\text{lb}) + \begin{pmatrix}\text{3 yr}\\ \text{discounted}\\ \text{fuel}\\ \text{savings}\end{pmatrix}}{(\text{wt of nanocomposite body panels})} \quad (3)$$

Figure 7 summarizes the required cost per pound and resulting environmental implications for various nanocomposite substitution scenarios. For example, at point A, nanocomposite is substituted for steel in 70% of all motor vehicle body panels. This substitution results in a 52% primary weight reduction in those panels. The estimated required cost per pound for materials, processing, and production is \$6.50/lb. Assuming that the substitution is made across all 210 million light-duty vehicles on the road, annual petroleum production would be reduced by 5.5 billion gal, annual CO_2 production during vehicle use would be reduced by 47 million t, and CO_2 equivalents from petroleum production would be reduced by 14 million t. Our analysis indicates that the materials, processing, and assembly of the nanocomposite body panels would be worth \$4.60/lb for a 38% weight reduction and \$10.30/lb for a 67% weight reduction. The cost of producing and assembling body components with this nanocomposite would likely be a good deal less than \$10.30/lb but might not be less than \$4.60/lb. Assembly costs may not change substantially unless the material substitution is accompanied by design changes that include part consolidation. Therefore, competitiveness of the nanocomposite is unlikely to be helped by cheaper assembly. Table 10 compares the required cost per pound with and without assembly for the nanocomposite lower and upper bounds.

Other Important Implications. Several important environmental and performance implications have not been considered in this analysis. Two implications important in conducting a vehicle life cycle analysis include recyclability and repairability. Approximately 80% of the weight of a motor vehicle is recycled; however, the majority of the plastics are shredded and landfilled (*32*). Polymer experts assert that the clay nanocomposite can be recycled without significant changes to the material. The composite is stable to recycling because the aspect ratio between the matrix and the montmorillonite clay will not be reduced, as it would be in a composite filled with long glass fibers, for example. Furthermore, the ability to remove complete body panels comprised of a uniform polymeric composite makes recycling feasible. A more complete life cycle analysis would compare the economic and environmental impacts associated with recycling steel, aluminum, and nanocomposites. There are mixed predictions about the effect of composite substitution on repair costs. For example, significant part integration may lead to larger repair costs, whereas less damage in low-energy collisions may lead to repair costs similar to current levels (*33*, *34*). We did not include a repair cost differential in our panel-for-panel substitution scenario. Repair issues for composite components with a more substantial structural role, such as in the BIW, would need to be considered. Another important requirement in automotive design is that of safety. Most experts agree that passenger safety increases with vehicle weight. However, Greene and Keller argue that proportionally reducing the mass of all vehicles will not necessarily increase risk; rather there is evidence that it may actually improve safety (*2*). Each of these topics, as well as other performance requirements, will need to be considered in the actual design of automotive body panels.

TABLE 10. Estimated Required Cost per Pound of Alternative Materials

costs included	nano, lower (\$/lb)	nano, upper (\$/lb)
materials, processing, and assembly	4.60	10.30
materials, processing	3.70	8.20

Discussion

We used a steady-state model to estimated potential economic and environmental implications of substituting a nanoclay−polypropylene polymeric composite or aluminum for steel in motor vehicle body panels on a part-by-part basis. A major material substitution in the automotive industry would have to occur incrementally rather than in a radical and disruptive complete material substitution. Realistically, the steady-state results presented here would take a long time to be realized. A more robust model, such as fleet-based life cycle assessment presented by Field et al. (*29*), can be used to estimate environmental implications over time. Consideration of complete BIW material substitution or radical body design changes, such as a hypercar vehicle design, that optimize performance based on the specific properties of nanocomposites may lead to considerably different nanocomposite results.

Current levels of uncertainty concerning the performance of the nanocomposite lead to constructing lower and upper bounds. Uncertainty about the costs of using this material in body fabrication lead to estimating the value of this material as a function of its efficiency and the amount of steel that it can replace. At the upper bound 67% efficiency, the nanocomposite substitution would be worth a little more than $8/lb in materials and processing costs with assembly adding a further $2/lb. At a lower bound 38% efficiency, this substitution would be worth just less than $4/lb in materials and processing costs with assembly adding a further $1/lb. Thus, even near the lower-bound value, the nanocomposite could be a competitive material that would increase fuel economy at low cost. Greater fuel economy leads to potentially large economic and environmental benefits. The CO_2 reduction during the lifetime use of motor vehicles is a large potential benefit. However, U.S. consumers have little interest in greater fuel economy, and so this technology is unlikely to be developed and employed in this application without government intervention.

Aluminum costs less than the nanocomposite and offers better performance than the lower bound nanocomposite, although the nanocomposite is better at the upper bound. We did not consider other materials that have already demonstrated significant weight savings potential in automotive applications. Examples include advanced high strength steel, magnesium, glass fiber-reinforced polymers, carbon fiber-reinforced polymers, metal matrix composites, and titanium. Nor did we consider other nanocomposites such as composites reinforced with synthetic carbon nanotubes. The future composition of the motor vehicle will be determined by intensive competition among the future cost/performance ratios of candidate materials. The production costs for steel are much lower than alternative materials and steel is an ideal material for mass production of vehicles. Our analysis shows that aluminum offers considerable weight reduction and environmental savings as compared to steel, but vehicle manufacturers have not made the substitution. We conclude that steel has considerable advantages, including a long history of producing a satisfactory product. To displace steel, a lightweight material must offer much larger savings or other advantages (such as satisfying a high CAFE standard) than is required to pay for its additional cost and satisfy the many other structural and functional requirements in order to induce manufacturers to re-engineer their vehicles for the new material. One major advantage of polymer composites over metals is the ability to fabricate aesthetically pleasing complex shapes. While this is not an environmental savings, this benefit coupled with higher fuel economy could entice consumers to purchase the lower weight vehicles, thus reducing environmental impact.

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