

# Triple Safety: Lightweighting Automobiles to Improve Occupant, Highway, and Global Safety

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## ABSTRACT

Automobiles' negative impact on human health and welfare includes traffic-related deaths and injuries as well as the deaths and injuries caused by automobiles' contribution to climate change and other global environmental degradation. This paper explores solutions that both enhance vehicle performance and reduce environmental impacts, and focuses on demonstrating the ability of lightweight vehicles to provide such a solution. Some controversy exists around the question of whether lighter and more fuel-efficient vehicles can be as safe as traditional vehicles. Recent research reviewed in this paper indicates that several solutions exist that can both improve efficiency and thereby global safety, and maintain (or even improve) highway safety.

## INTRODUCTION

The notion of "safety" in regards to automobiles has become more complex as global consciousness of climate change's dangers has increased and the importance of automobiles in the climate change equation has become apparent (the Intergovernmental Panel on Climate Change (IPCC) 2007 report found that light duty vehicles are responsible for about 10% of all energy-related greenhouse gas emissions and trucks responsible for about 6% [IPCC 2007]). The predominant public belief is that the two "safeties" are inevitably at loggerheads: that changing cars to be much more efficient will inevitably compromise on-the-road safety (Hewlett 2006). This argument has been especially apparent in recent debates on Corporate Average Fuel Economy (CAFE) legislation in the United States.

The statistics on automotive-related death are indeed harrowing: 43,000 fatalities in America last year, and more than 1.2 million worldwide (NHTSA 2007, WHO 2007). The statistics on climate-change-related death are harrowing too, although the relationship between climate change and death is often indirect and difficult to prove. The World Health Organization conservatively

calculated that climate change caused 150,000 thousand deaths worldwide in 2000 (WHO 2002). The most recent reports from the IPCC predict that climate change could threaten more than two billion people with fatal water shortages, disease, famine, and more—orders of magnitude greater than the potential impact on human health as a result of automobile accidents (IPCC 2007).

Sacrificing either highway safety or greenhouse-gas emissions goals would be both irresponsible and unnecessary. Several solutions exist that both enhance human safety (for automobile occupants and other road users) while reducing environmental impacts. Automakers and communities should pursue systems and technologies that improve all safety simultaneously instead of creating a situation that pits highway safety and greenhouse-gas emissions goals against each other. Several options already exist and are mentioned below. This paper will focus on one of the more controversial solutions to both safety problems: the lightweighting of automobiles.

Creating lightweight and safe automobiles is not always simple, but it is both necessary and possible. Our first section reviews options besides lightweighting that can enhance safety and efficiency. Our second section presents analysis demonstrating the value of lightweighting to improve vehicle efficiency. Next, we give an overview of the statistical literature for and against the claim that lighter cars inherently lead to more highway deaths. Finally, we review the feasibility of making lightweight and safe parts and full vehicles using several on-the-road examples from the U.S. and European automobile industries.

## MULTIPLE SOLUTIONS EXIST

No one single approach can adequately reduce the potential dangers associated with automobile accidents as well as automobiles' environmental impacts. Many different, mutually beneficial, solutions exist. Some of the simplest solutions are presented below.

## REDUCING HIGHWAY DEATHS AND EMISSIONS BY SPENDING LESS TIME ON THE ROAD

The first, most direct way to reduce the number of traffic-related deaths while reducing automobiles' environmental impact is to have less traffic. This can take the form of more and better public transportation or communities whose design encourages less driving—or both. One study found that in the United States, using public transportation is about 1/20th as dangerous as using a private automobile and that the use of public transportation results in a net saving of 1.4B gallons of oil (APTA 2007). However, Americans are driving more often and farther as the population and suburbs expand. U.S. highway miles rose 21% between 1992 and 2002 (BTS 2003), and in developing countries such as China and India, car ownership is expected to rise 67% over 2006 levels by 2010 (Chinanews 2006). A combination of policy, green planning, transportation strategy, urban design, and individual education is needed to address the tremendous growth in driving on earth.

## REDUCING HIGHWAY DEATHS AND EMISSIONS BY MAKING AUTOMOBILES SAFER AND CLEANER

Simultaneously making cars less dangerous and less polluting is complex, but again, several options do exist. One option is to improve vehicle maintenance, especially in developing nations. Proper and timely maintenance can ensure that cars do not emit more greenhouse gases and other pollutants than they were designed to; as vehicles age and parts like catalytic converters wear out, they release more harmful emissions. Maintenance also ensures that vehicles function as designed to protect their occupants.

Another viable next option is to reduce speed limits, or enforce the speed limits that already exist.

Other clever possibilities to reduce emissions while enhancing safety probably exist. But for the remainder of this paper, we will focus on lightweighting automobiles.

## LIGHTWEIGHTING

Several barriers to lightweighting exist, such as the cost and effort of training automotive engineers and technicians to use the alternative lightweight materials, such as aluminum and carbon fiber reinforced composites (CFRCs), and ramping up production of hitherto modest materials industries. These challenges are being tackled by ongoing Rocky Mountain Institute (RMI) research and work and will be the topics of subsequent papers.

One of the most widely cited barriers to lightweighting is a possible compromise of safety. This issue has long been the source of years of discussion and controversy. During the past five years, however, several important

studies were released and concept cars built that have helped educate decision makers and prove that lightweighting does not lead to a reduction in highway safety.

## CLIMATE CHANGE: LIGHTWEIGHTING CAN SIGNIFICANTLY REDUCE VEHICLE EMISSIONS

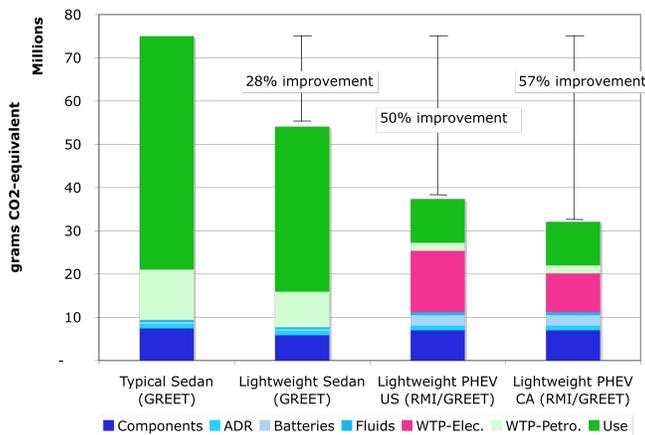
Lightweighting vehicles can lead to dramatic fuel savings. RMI's extensive automotive research indicates that, in general, a 10% reduction in weight can lead to a 7% increase in fuel economy (Aluminum Association 2007). RMI's research also shows that when lightweighting is done aggressively, weight savings (and fuel economy gains) are compounded. For example, a car that is several hundred pounds lighter than a traditional model can get the same performance from a smaller engine. RMI research indicates that aggressive lightweighting of vehicles combined with advanced powertrain technologies such as plug-in hybrid electric vehicles (PHEVs) can significantly reduce greenhouse-gas emissions (see Figure 1).

Figure 1 shows greenhouse gases emitted throughout the lifecycles of several vehicles: a typical sedan (21 mpg), a lightweight sedan (30 mpg), and a lightweight plug-in hybrid vehicle charged using both U.S. average and California grids (effective "gasoline economy" 166 mpg).

This Figure shows the greenhouse gas emissions for each vehicle across the entire lifecycle: from the mining of the materials to the recycling of the batteries and every step between. This approach (called Life Cycle Assessment) helps protect against burden shifting from one phase of the vehicles life to another. The life cycle approach shown in Figure 1 also demonstrates that even if the impact of the vehicle materials was eliminated entirely, if they were from completely recycled sources and used renewable energy for processing, the overall reduction in greenhouse gases would be less than the reduction achieved from lightweighting the typical sedan.

The typical and lightweight sedan data are taken from Argonne National Lab's GREET model (GREET 2007); figures for the two PHEVs were ascertained using an RMI vehicle modeling and simulation tool that has been validated for numerous existing vehicles in conjunction with GREET automotive life-cycle analysis software. The graph shows that lightweighting is a powerful tool to reduce greenhouse-gas emissions on its own. Lightweighting becomes even more powerful when combined with advanced technologies like a PHEV powertrain because the petroleum savings are compounded and because the PHEV needs a much smaller (and less expensive) battery to meet performance needs. Table 1 gives proposed lightweight PHEV parameters.

**Figure 1:** Greenhouse-Gas Emissions from Four Vehicles: Sedan, Lightweight Sedan, and Plug-In Sedan (US and CA). Source: GREET and RMI Analysis.



**Table 1:** Parameters for RMI Lightweight PHEV. Source: RMI Analysis.

Parameter	RMI PHEV Value
Curb Mass	1000 kg
Frontal Area	2.3 m <sup>2</sup>
C <sub>d</sub>	0.26
Rolling Resistance	0.007
Mean Hybrid Drive $\eta$	29%
0-60 Time	9.4 sec
Front Engine	1.2L, 3 cylinder, direct injection, transverse
Transmission	CVT or DCT, Automatic
Rear Electric Drive	20 kW, integral gear reduction, differential
Battery System	7 kWh (end-of-life), 23 kW peak DC
Battery Life	10 years / 150,000 miles
Fuel Economy in Gas Mode	60 mpg EPA combined
Grid: Gasoline Energy	55:45
EV Range	30 miles
EV Energy Consumption	792,000 J/mi (at the wall plug)

Certainly lightweight materials—such as aluminum or CFRCs and hybrid battery materials require more energy and emissions to produce per pound. However, the lightweight vehicle uses half as many pounds and has such large fuel savings that the extra emissions caused by the alternate materials are clearly outweighed by the emissions saved by halving the pounds that go into the vehicle and improving the use efficiency. Several other studies have confirmed that lightweighting will reduce a vehicle’s lifetime greenhouse-gas emissions (ANL 1995, Dhingra 1999, Schexnayder 2001).

If lightweight vehicles replaced every car in the world today, the most conservative estimate of improvement in greenhouse gas emissions from lightweighting (28%,

from lightweighting with no power train changes) would lead to a ~5% reduction in world greenhouse-gas emissions and if instituted in the United States would reduce national greenhouse-gas emissions by ~7%. The greatest improvement estimate (57%, the lightweight PHEV with a California-type grid supplying electricity) could lead to a ~11% reduction in global greenhouse-gas emissions.

#### LIGHTWEIGHTING AND HIGHWAY SAFETY: STATISTICAL AND EMPIRICAL DATA INDICATE NO DANGER FROM LIGHTWEIGHTING

Determining the safety consequences of lightweighting vehicles involves two separate questions: first, is there a direct relationship between the weight of a car and the safety of the occupants? And second, do the materials necessary for building lightweight vehicles (aluminum, high-strength steels, and composites) have the characteristics required for building cars as safe or safer than traditional mild steel cars?

The former question has been the subject of far more controversy than the latter. This section will address both questions through a review of academic papers, technical reports, and the performance of existing examples of lightweight cars.

#### The Relationship Between Weight and Safety

“Safety” can mean several things when discussing automobiles. First, it can refer to the “crashworthiness” of a vehicle, or the occupants’ chance of surviving a crash. Second, it can refer to the “crash avoidance” of a vehicle—the chance that a car will get into a crash. Third, it can refer to the “aggressivity,” or the likelihood that the car will kill someone else in a crash.

Crash avoidance, the ability of the car not to crash in the first place, is largely weight independent so it will not be addressed in detail in this section. Crash avoidance is related to features such as agility, anti-lock brakes, and electronic stability control, etc.

When they think about crashworthiness, both consumers and those with more extensive involvement in automotive safety often revert to thinking in terms of “the laws of physics”—if a heavier object hits a lighter one, the lighter one will rebound farther/faster or suffer more damage. This kind of thinking is based on high-school physics lessons, where students are taught about collisions between objects like, say, a bowling ball and a billiard ball. Automobile accidents are quite different from simple collisions between balls.

First, cars are not simple, solid objects; they have crush zones and structural features designed to absorb impacts. In other words, length and design are more important than weight. While a light car does tend to

experience a faster deceleration than a heavy car in a two-car crash, this is only one of several factors in determining occupant safety.

Second, fatalities are generally the result of one of the following events: intrusion of another vehicle or object into the passenger compartment, rollover, and failure of restraints (such as seatbelts or airbags) to keep passengers out of contact with hard parts of the vehicle (Wenzel and Ross 2006). None of these events are related to the weight of the vehicle, but to the length, design, and safety features. For example, between 2000 and 2006, fatality rates in new SUVs went from 46 to 19 fatalities per million vehicles. That reduction was attributed to manufacturers' design changes, especially the lowering of the center of gravity and an increase in trackwidth (both trends related to the rising popularity of cross-overs) and they occurred without major changes in weight (Wenzel and Ross 2006).

Third, deaths from frontal collisions between two vehicles—the kind most applicable to the “basic laws of physics” argument—are becoming less frequent. In 1980 they were ~2,600 frontal-collision deaths/year, but by 2000, there were only 1,300 (Ross and Wenzel 2005). This is due to improvements in safety design of vehicles. The following section outlines the most important research in the debate about weight and crashworthiness.

The most recent innovation in relevant research has been the disaggregation of the weight and size of a car in statistical analysis. These two metrics are often correlated (larger cars generally weigh more), but the best analyses have shown that size, independent of weight, matters more for safety. The weight of a vehicle is strongly correlated with aggressivity, but it is not correlated with crashworthiness or crash avoidance. (A more aggressive car is not safer, just more dangerous). This relationship has been discussed since the 1970s. At the Third International Congress of Automotive Safety several researchers (including first administrator of NHSTA William Haddon, Jr. and future Insurance Institute for Highway Safety President Brian O'Neill) reported that:

“...for vehicles using the same roads these relationships suggest a crashworthiness design concept for the intervehicular crashes that regards increases in vehicle size as primarily protective, and increases in vehicle weight as primarily hostile, indicating the desirability of relatively sizeable but not heavy vehicles.” (Public Citizen 2004)

Since the '70s, research has challenged this notion, and since the mid-90s, the debate has been renewed academically. The following section briefly describes the most important research on both sides of the safety versus weight argument.

## Summary of the Debate

A handful of studies are cited in terms of major decision making. These studies, which support the argument that weight confers safety, are briefly summarized and major direct criticisms of them are offered below. Recent studies that argue that safety can be achieved independent of weight are listed in the next section.

### The Weight Confers Safety Argument

The most prominent studies, and their criticisms, are summarized in the following pages.

**Crandall and Graham, 1989.** Crandall and Graham's study created a regression model to predict traffic fatalities based on projected vehicle weight. They used data for fatalities from 1947 to 1981 to build their model. They found that increased weight correlated with decreased fatalities and that the CAFÉ standards put in place in 1978 would lead to a 14–28% increase in fatalities.

**Critics of Crandall and Graham.** Wenzel and Ross (2006) pointed out that Crandall and Graham used data that include only four years where CAFE had been in effect, so fuel economy had improved little while weight had increased. Kazzhoum (1994) critiqued Crandall and Graham and reran their analysis using data from 1985 to 1989, which generated the result that increased car weight caused the number of fatalities in single-car crashes to go up. Ahmad and Greene (2004) reexamined Crandall and Graham's studies using data from 1966 to 2002, and found that the statistics could not support the assertion that increased fuel economy has led to a greater number of traffic fatalities.

**Evans (1992/1994/2004).** Studies by Evans largely focus on the positive relationship between change in momentum of the occupants of a vehicle and risk for injury or fatality. In 2004, he found that the likelihood for fatality increases as the mass ratio between vehicles in two-car collisions increases.

**Criticisms of Evans.** Wenzel and Ross (2006) criticized Evans for, above all, not distinguishing between vehicle size and weight. They also criticized him for not distinguishing aggressiveness from protectiveness: “Using Evans' ratio, a car design that tends to kill others appears as a safety attribute!” Finally, they point out that deaths in two-car frontal crashes declined from 36% to 14% of all driver fatalities between 1980 and 2004. The decline was due to improved crashworthiness of cars from increased seatbelt/airbag use and improved frontal design, and because of the rising number of SUVs and trucks on the roads. Therefore, not only does Evans ignore the relationship between design and safety, he also irresponsibly draws sweeping conclusions from a shrinking segment of fatal crashes. Public Citizen (2004)

refers to Evans as an “industry apologist and CEI [Competitive Enterprise Institute] consultant” and also accuse him of ignoring suggestive findings in his own data, such as pick-up trucks and SUVs having higher fatality rates than passenger cars and minivans of comparable weight.

**Kahane 1997/2003/2004.** Performed for the National Highway Traffic Safety Association (NHTSA), the Kahane study is the most widely cited research about the relationship between weight and safety. It was especially prevalent during discussions about the impact of CAFÉ on safety. The 2003 study was an update and refinement to the 1997 studies, and the 2004 study was an attempt to respond to criticisms of the 1997 and 2003 studies. Kahane performed a logistic regression analysis of fatalities per billion miles. He found that fatality rates increased as weight decreased. Specifically, he found that a 100-lb reduction in vehicles would lead to more than 1,000 extra fatalities in 1999.

**Criticisms of Kahane.** Several documents have been dedicated completely to critiquing Kahane’s findings, including Public Citizen 2004, and Van Auken and Zellner 2002, 2003, 2004, and 2005.

A National Academy of Sciences panel asked to review the 1997 Kahane study was unable to endorse the quantitative conclusions of the report due to “the large uncertainties associated with the results—uncertainties related both to the estimates and to the choice of the analytical model used to make the estimates.” Public Citizen (2004) criticized Kahane for not addressing the difference between size and weight. They also pointed out that in several places he himself finds a correlation between other factors, such as height of force and frontal rigidity and fatality (i.e., size and design), and was irresponsible not to follow these findings to their natural conclusion: a distinction between size and weight. These criticisms are mirrored in Wenzel and Ross (2006). Public Citizen and Van Auken and Zellner (2003) question Kahane’s exclusion of 200/300 series trucks, full size vans, and all two-door vehicles. Van Auken and Zellner (2002/2003), with funding from Honda, repeated Kahane’s 1997 analysis using Kahane’s general methodology but with more inclusive and updated data, and more articulated metrics (e.g., distinguishing size and weight). They found there was no correlation between weight and safety (2002), and that safety increased with size and decreased with weight (2003). These findings are further detailed below. Greene (2006) criticized Kahane’s 2003 study for refusing to respond to concerns raised in Van Auken and Zellner’s 2002 study.

Research since Kahane: Safety Relies on Many Factors, Principally Size and Design

Several studies, many mentioned above as critiques, have found that safety is a result of not weight but the

size of a vehicle (wheelbase and track length are the most common metrics of size) and its design (including crash absorbing structures, center of gravity, and safety features such as seatbelts and airbags). The three most comprehensive studies are described below.

**Van Auken and Zellner (Dynamic Research Inc.) 2002/2003/ 2004/2005.** In the wake of the Kahane report (1997), Honda commissioned Dynamic Research, Inc. (DRI) to redo Kahane’s study using more up-to-date data and investigate other factors related to safety. In the 2002 study, they looked at Kahane’s six types of crashes with the same controls and found that a weight reduction for all passenger cars and light trucks would result in a net decrease of two fatalities of the 37,633 in 1999, a statistically insignificant number. This result is due to opposing trends in the data: the passenger cars’ reduction adds 34 deaths while light trucks’ reduction subtracts 36, and 100-lb reductions increase fatalities in certain types of crashes and decrease fatalities in others.

In the 2003 study, DRI disaggregated vehicle weight from size. They found that overall fatalities (fatalities of both the driver of the vehicle in question and others using the roads) increase as weight increases, and that they decrease as wheelbase and track increase. Since the weight and size are roughly correlated in traditional vehicles, these two opposing forces are almost exactly offset by each other and explain the statistical insignificance of the 2002 results. They concluded: “Therefore, based on these results...the number of traffic fatalities in the future could be reduced by decreasing the passenger vehicle fleet weight while maintaining the wheelbase and track constant.” More specific interesting findings include that a 100-lb reduction in car weight (holding wheelbase and track constant):

1. Does not have a statistically significant effect on crashworthiness (the occupant’s safety) in two vehicle crashes,
2. Decreases the number of fatalities (for both cars’ occupants) in two-car crashes,
3. Does not have a statistically significant effect on crashworthiness and compatibility (total fatalities) in other types of crashes, and
4. Decreases the number of car-light truck crashes per induced exposure (improves crash avoidance).

A 100-lb reduction in light trucks, with the same constraints:

1. Decreases the risk of fatality due to crashworthiness in rollovers,
2. Decreases the risk of fatality due to crashworthiness and compatibility (for both trucks’ occupants) in crashes with another light truck,

3. Does not have a statistically significant affect on light truck crashworthiness and compatibility in other types of crashes (for all road users), and
4. Decreases the number of hit-object crashes and crashes per induced exposure (improves crashworthiness).

These findings shed important light on the implications of weight reduction for specific vehicles, not the fleet as a whole. There is an emphasis on net fatalities in many of these studies because they were intended to inform highway safety policy makers whose interest is the overall safety of the population, not to inform individual consumers purchasing a car.

Van Auken and Zellner 2004/5 confirmed and refined their earlier studies, and responded to comments from Kahane.

Dynamic Research, Inc. also performed a study at the behest of the Automotive Aluminum Association. They modeled crashes of a “lightweight” SUV and an elongated SUV against baseline crash data. They found that a weight reduction in the larger of two vehicles in a two-vehicle crash, or an increase in frontal crush zone of the SUV, could reduce overall fatalities by 15–20%.

It is important to note that in Van Auken and Zellner 2002, and more explicitly in 2003, they refrain from endorsing their findings for weight reductions “much larger than” 100 lbs, and suggest further study be performed to confirm that the safety trends extend to large weight reductions. RMI is currently embarking on such research.

**Robertson 2006.** Robertson’s research found that existing car models with the same turning radius (wheelbase) can have widely divergent weights and crashworthiness. He found that higher stability ratios, longer turning distance (wheel base), and “good” crashworthiness design are the most important factors to decreasing risk of fatalities. He found that if all vehicles were reduced to the lowest weight per wheelbase, traffic fatalities would have been reduced 28% (and fuel usage reduced 16%) for 2005. If all vehicles had crashworthiness and stability equal to those of the top-rated vehicles in their wheelbase classes, more than half of traffic deaths could have been prevented.

**Wenzel and Ross 2001/2002.** Wenzel and Ross broke down fatalities by driver of the vehicle in question, and driver/occupants of other vehicles involved in the collision by make and model. This approach showed that the class of a vehicle, and even the model, has a large impact on risk independent of weight. Specific findings include:

1. The safest midsize/large cars are as safe as the safest SUV for the driver. The average midsize and

large cars are just as safe as the average SUV. However, SUVs impose the greatest risk for others, and have a 30–40% greater combined risk than cars.

2. Minivans are the safest class of cars, perhaps because of driver demographics, but also because they are built on a car chassis making them safer for their drivers and others.
3. The car-based Jeep Cherokee has a 20% smaller risk to its driver than the truck-based Cherokee.
4. Pick-ups are the least safe. They are also the most aggressive. Though pick-ups and SUVs are more likely to kill the other driver in a two-vehicle collision, that doesn’t mean they are safer: pick-up and SUV drivers are more likely to die in stable-object collisions.

These risks are substantially due to design.

#### ACTIVE SAFETY FEATURES: THE NEXT WAVE IN SAFETY DESIGN HAS NOTHING TO DO WITH WEIGHT OR SIZE

Government agencies and automakers are currently developing a new generation of “active” safety features. These are technologies that prevent cars from crashing in the first place, making weight an even more obsolete safety issue. They include lasers that monitor nearby traffic and lasers that monitor the driver’s eye-lid position, to determine if the driver is getting sleepy. These active safety cars would take control of the vehicle if the driver started to make a mistake. Cars would be able to communicate with each other, thus managing the road safely. While these safety features are still in the experimental phase, the automotive industry is moving rapidly to explore and develop active safety features (SAE 2007).

In addition, a few active safety features are already widely in use. They include a feature that will soon be required in all vehicles: electronic stability control (ESC), which uses computer-controlled braking of individual wheels to help the driver keep control in emergency situations where the driver would otherwise spin out or plow out. The National Highway Traffic Safety Administration predicts that ESC will reduce car crashes by 34% and SUV crashes by 59%, saving between 5,300 and 9,600 lives annually, around one-fifth of traffic-related deaths (NHTSA 2007[2]). None of the active safety features depend on weight.

#### SUMMARY OF WEIGHT AND SAFETY

Though determining a “safety” factor for a vehicle is complex, the most up-to-date research has shown that increases in size—not increases in weight—are directly correlated with safety, as is good design.

## **MATERIALS: CAN LIGHTWEIGHT OPTIONS MAKE THE SAFETY AND ENVIRONMENTAL CUT?**

Extensive tests have been done to determine if lightweight materials can provide the same or better safety characteristics as traditional car materials. All these lightweight materials already exist in current, on-the-market cars that have passed American or E.U. safety tests. Little debate exists around the potential of these materials to perform as well as steel, given proper design. Many of these materials are currently used in conjunction with mild steel, or in conjunction with each other.

### **ALUMINUM: ALREADY WIDELY IN USE**

Pound for pound, aluminum structures can be up to 2.5 times as strong as steel, and they can absorb up to two times as much energy in a crash (Larkin 2004). Aluminum also deforms more predictably than steel. The best example of aluminum's safety attributes is found in the Audi A8, an aluminum-heavy luxury vehicle. The A8 has the safest crash test ratings at 35 mph in its class. Aluminum use is growing in the automotive industry; it recently surpassed plastic to become the third most common material in cars (Aluminum Association 2007).

As part of the Partnership for the Next Generation Vehicle, Ford designed a 2,000-lb Taurus (a normal Taurus weighs 3,318 lbs) that relied on 733 lbs of aluminum to achieve much of the weight reduction. It passed all crash tests applicable to federal motor vehicle safety standards, and received scores similar to or better than the steel-bodied Taurus. According to a Ford Motor Company engineer, "Ford engineers now know that aluminum meets the same federal crash test standards as steel given the proper design and construction methods" (Larkin 2004).

A few other examples of aluminum's proven affect on safety:

1. Volkswagen developed the multi-material-designed CCO concept car. The frontal and side crash zones, mainly aluminum, passed safety standards (Friedrich 2003).
2. The Honda Insight, also all-aluminum, is 40% lighter than a steel counterpart and passed all safety tests.

### **ADVANCED HIGH-STRENGTH STEEL: GROWING IN USE**

The use of high-strength, lightweight steel is growing in cars, often in conjunction with aluminum or composites as part of a multi-material design. Its safety has been proven by several studies and examples.

BMW has embraced different alloys of higher strength steel. The BMW 3 series' strength has gone from 178 N/mm<sup>2</sup> to 294 N/mm<sup>2</sup> as a result of the use of lighter steel alloys combined with some aluminum alloys and plastics. BMW uses baking and other treatments to further improve strength of lightweight steel (Pfestorf, et al. 2006)

Ford's IMPACT program successfully redesigned an F-150 for 25% weight savings and no performance compromises (including safety). Ford's success relied mostly on the use of advanced and high-strength steels. About 60% of the innovations developed during the IMPACT program have made their way into production vehicles (Geck, et al. 2007).

A few other examples of high-strength steel's affect on safety:

1. Li, Lin, Jiang, and Chen found that, in simulation, high-strength steel replacements for key crash-absorbing vehicle parts led to no safety compromises (Li, et al. 2003).
2. The Volvo 3CC electric concept car featured a high-strength steel space frame, which Volvo chose specifically for its combination of high safety and low weight (JEC Composites 2007).

### **COMPOSITES: WELL PROVEN IN TESTS, MAKING AN APPEARANCE ON THE ROAD**

Composites, a term that usually refers to carbon fiber reinforced plastics (CFRP), are the lightest of the three lightweight materials discussed here. CFRPs can absorb 10 times as much energy per pound in a crash as steel and use crush length more effectively and smoothly (Lovins 2004). Their effect on safety has well been proven in laboratory tests, in their use in Formula One cars and aircraft, and even in production commercial vehicles.

Researchers with the Automotive Composites Consortium performed crash tests with a composite vehicle (glass-fiber reinforced polymers, weaker than carbon fiber reinforced) in 1996. The car passed a 35-mph barrier crash test leading Alan Taub of Ford to remark, "This was the first demonstration that a composite front-end structure, designed for mass-production manufacturing, could display outstanding energy-management performance." And John Fillion of Chrysler Crop said, "There is no safety trade-off when you replace steel with a correctly designed composite part" (Ashley 1996).

The Automotive Composites Consortium (ACC), a group within USCAR, has continued research since 1996, building parts of out glass-fiber composites and refining them for optimized performance and manufacturing. Fiber-reinforced composites perform best when vehicle

design is optimized for their characteristics (e.g., they are usually stronger in one direction than another). ACC is modeling the performance of carbon fiber composites in conjunction with weaker glass fiber composite parts, and continues to research other lightweight materials as well (FreedomCAR 2007).

BMW found that CFRP are the perfect replacement for parts that were formerly made out of sheet metal because of improved functionality. BMW did tests on a 1-mm steel sheet, a 2-mm steel sheet, and a 1-mm steel/carbon composite laminate reinforced profile. The composite resisted almost twice the amount of force that was required to bend the 2-mm steel (Pfestorf, et al. 2006)

Other good examples of proven composite safety:

1. Mills, et al. (2002) developed a carbon fiber space frame with a torsional rigidity of 15,000 Nm/degree.
2. The 2005 Keonigsegg CCR is the fastest production car on the road, and its monocoque construction makes it very safe: during crash testing in Sweden, the CCR's impact structures absorbed considerable amounts of energy, resulting in only cosmetic damage to the car and very small impact forces on the dummies. (JEC Composites 2007[2]).
3. The 2004 Volvo 3CC electric concept car featured a combination of a high-strength steel space frame, composite sandwich floor panels, and a bonded one-piece carbon fiber shell that enhanced safety and made the vehicle light. Volvo had several safety design breakthroughs in the making of this car, including the "Volvo Safety Ride Down Concept" to overcome safety burdens small size (not small weight) (McLane 2005).
4. The SLR McLaren features carbon fiber composite construction adopted from Formula 1 racecars. The composite body provides rigidity and strength. In principal, the 1,768-lb McLaren could dissipate crash energy against a fixed barrier at 66 mph (Lovins, et al. 2004).
5. The all-composite Hypercar Revolution, according to industry standard simulations, showed that a 35-mph crash into a wall would not damage the passenger compartment—that's twice the speed of a crash that would total most cars. Also, the Revolution could protect its occupants from injury in a head-on collision with an SUV twice its weight with both cars going 30 mph (Lovins, et al. 2004).

## CONCLUSION

Much research remains to be done on the implications of weight change and no individual vehicle can be deemed safe without the rigorous safety tests that the developed world has come to expect and that the developing world will soon expect as well. But the research and examples highlighted in this paper indicate that lightweighting

automobiles can be a potent weapon against both climate change and traffic fatalities, and an important partner with the other policy and consumer choice solutions mentioned early in the paper. Consumer education to overcome past negative publicity about lightweight cars is a key part of this task. By working together, groups interested in each of these goals can achieve their missions and create a solution that, instead of sacrificing safety, protects more than either traffic safety advocates or environmental advocates could alone.

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