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Advanced, Lightweight Materials Development and Technology for Increasing Vehicle Efficiency

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"Fat men cannot run as fast as thin men, but we build most of our vehicles as though deadweight fat increased speed…. I cannot imagine where the delusion that weight means strength came from…." - Henry Ford

Introduction

As Amory Lovins, Chief Scientist at the Rocky Mountain Institute wrote, "The automotive industry is arguably the largest and most complex undertaking in industrial history. Its highly evolved production methods satisfy the conflicting demands of price, safety, performance, reliability, emissions, and market appeal." (2004)

However, ever-increasing government regulations on vehicle safety and pressure from consumers concerned with fuel economy and environmentalists concerned with emissions, car and truck manufacturers, and their suppliers, must turn to new technologies to help them achieve their goals of making vehicles stronger, lighter and more efficient.

Worldwide, vehicles consume oil at a rate of nearly 30 million barrels per day (McAuley, 2003). US vehicle registrations have climbed steadily from 110 million in 1940 to more than 200 million today. Global growth has been much more rapid, expanding from 130 million to more than 450 million during the same time period. Over the next 50 years, worldwide numbers are likely to increase 3-5 times, resulting in 2 to 3.5 billion light vehicle registrations (McAuley, 2003).

Environmental and sustainability consequences of the growing worldwide transportation sector will need to be addressed with new technological solutions. Without these improvements, increased consumption of petroleum will result in increased emissions of greenhouse gases, which contribute to global climate change. Currently, the combustion of fossil fuels in the U.S. transportation sector accounts for one-third of all CO_2 emissions, three-quarters of those emissions are due to road transportation (Bandivadekar, 2008).

Public policy is demanding reductions in fuel consumption and resultant GHG emissions. European passenger car manufacturers have already taken steps to increase fuel efficiency and thereby reduce CO_2 emissions, averaging 187g CO_2/km in 1995 to 140g/km in 2008. More aggressive targets are planned for a further reduction to 120g/km by 2012 (Weiss, 2000). This target emission level would translate to an average fuel economy slightly better than 45 miles per gallon. In the U.S., the Energy Independence and Security Act, the so-called Energy Bill, will require the U.S. auto industry to raise its Corporate Average Fuel Economy (CAFE) standards by 40%, to 35 miles per gallon by 2020. (Heywood, 2008)

To achieve these efficiency improvements, automakers are developing a wide array of advanced technologies. These include improvements to engines, drivetrains, transmissions and aerodynamics and utilization of hybrid-or-full electric power systems in conjunction with alternative fuels. But the most fundamental and effective means of improving efficiency is accomplished by the reduction of vehicle mass.

Reducing vehicle size and weight can significantly reduce fuel consumption. By examining manufacturer's specifications for combined city/highway (55/45) fuel consumption and curb weights for each light-duty vehicle offered in the U.S. in 2005, Bandivadekar et al (2008) revealed the direct correlation between curb weight and fuel consumption. (Figure 1)

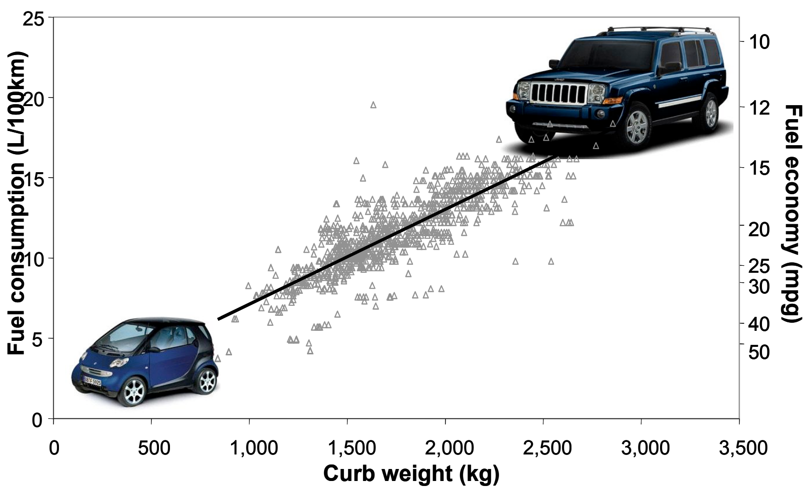

Figure 1. Curb weight and fuel consumption of U.S. model year 2005 vehicles (Bandivadekar, 2008)

Every 10% of weight reduced from the average new car or light truck can cut fuel consumption by 6.9% (Bandivadekar, 2008). These mass reductions can be accomplished by:

- Vehicle design changes
- Vehicle downsizing
- Lightweight material substitution

Obvious, but often overlooked, simple vehicle design changes can significantly reduce mass. These changes range from removal of unnecessary systems, such as heated power seating, to more aggressive part integration and optimization techniques. However, consumers may object to loss of certain “creature comforts” and the phenomenon of “feature creep” - adding more and more functionality year-after-year - which tends to increase vehicle mass. (Heywood, 2008)

Reducing vehicle size, or efficiently repackaging to maintain required occupant and cargo volume, is another effective technique to reduce mass. This is can be difficult, as market-driven demands for larger vehicles, has resulted in increases in the average size of vehicles year-after-year. (Figure 2)

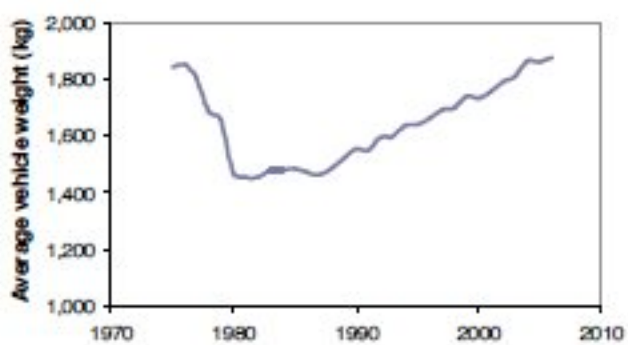

Figure 2. Historical sales-weighted average new U.S. light-duty vehicle weight 1975–2006 (Bandivadekar, 2008)

Much promise lies with advanced materials technologies utilizing high strength, lightweight engineering alloys or composites to reduce vehicle body structure mass that can be amplified throughout the vehicle with lighter drivetrains and subsystems. However, many of these advanced materials have seen very limited use in production, due to higher material costs and lack of compatibility with existing manufacturing processes. This paper will discuss motivations, trends, studies and developments in utilizing lightweight engineering materials for vehicle mass reduction.

Energy Transfer In A Vehicle

Vehicles require only a small fraction of their maximum power output to maintain their speed during steady-state cruising. Peak power is needed during high-load driving conditions and hard acceleration, such as towing, passing, or climbing steep inclines. The power required for a given level of acceleration can be simplified (not taking into account such other factors as aerodynamic drag, rolling resistance, and motor efficiency) by the vehicle's rate of change of kinetic energy:

$$P_{acc} = \frac{m}{2} \bullet \frac{\left(v_1^2 - v_0^2\right)}{t} \qquad \textit{(Equation 1)}$$

where m = mass of the vehicle and its occupants, v_1 is the final velocity, v_0 is the starting velocity, and t is the time elapsed to reach v_1 from v_0.

Mass is also a primary determinant of power while climbing a grade:

$$P_{hill} = m \bullet g \bullet v \bullet \sin(\theta) \qquad \textit{(Equation 2)}$$

where g is the acceleration of gravity and θ is the angle of the incline.

It is clear from these simple equations that the peak power required is directly proportional to the mass of the vehicle. Indeed, studies show that reducing vehicle mass 10% lowers power required to maintain 90 km/h on a 6.5% grade at gross mass by ~6% for 5-occupant vehicles with curb mass ~1000 kg and the power required for 8.5 second 0–100 km/h acceleration at test mass by ~8.5% (Malin, 2007). Additionally, rolling resistance – the energy dissipated through frictional heating in tire deformation - is also proportional to mass. Cramer (2002) states, "reducing mass is the highest-leverage means of reducing peak power requirements for vehicle designers."

Energy Conversion Losses

Only about 15% of the energy from the fuel is utilized to move a vehicle down the road or run useful accessories, such as air conditioning. (Heywood, 2008). In other terms, it takes about 5-7 units of total fuel energy to deliver 1 unit of energy to the wheels of the conventional automobile (Lovins, 2004). The remainder of the energy is lost to combustion (engine), driveline and aerodynamic frictional inefficiencies. Figure 3 depicts the energy conversion efficiencies within a vehicle. Descriptions of the main losses, along with technologies for improved performance, are listed below, taken from the US D.O.E. Office of Energy Efficiency and Renewable Energy website: *Energy Losses in a Vehicle* – "Advanced Technologies and Energy Efficiency," http://www.fueleconomy.gov/feg/atv.shtml .

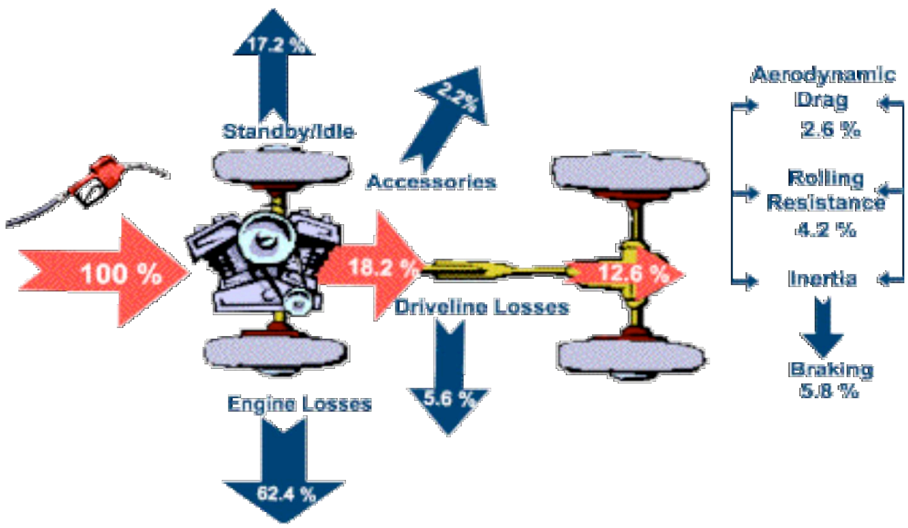

Figure 3. Overview of Energy Conversion Efficiencies in a Vehicle
(Source: http://www.fueleconomy.gov/feg/atv.shtml)

Engine Losses - 62.4%

In gasoline-powered vehicles, over 60% of the fuel's energy is lost in the internal combustion engine (ICE). Heat-to-work conversion losses, engine friction and wasted heat are all sources of inefficiencies. Advanced engine technologies, such as variable valve timing and lift, turbocharging, direct fuel injection, and cylinder deactivation can be used to reduce these losses.

Idling Losses - 17.2%

In urban driving, significant energy is lost to idling while stopped or in traffic. Integrated starter/generator systems can help reduce these *losses by automatically turning the engine off when the vehicle comes to a stop, and re-starting it instantaneously when the accelerator is pressed.*

Accessories - 2.2%

Air conditioning, power steering, windshield wipers, and other accessories use energy generated from the engine. Fuel economy improvements of up to 1% may be achievable with more efficient alternator systems and power steering pumps.

Driveline Losses - 5.6%

Energy is lost in the transmission and other parts of the driveline, typically due to friction between moving parts. Technologies, such as automated manual transmissions and continuously variable transmissions, are being developed to reduce these losses.

Aerodynamic Drag - 2.6 %

Vehicle drag is proportional to the square of the vehicle's speed – less energy at lower speeds and progressively more as speed increases. Drag is directly related to the vehicle's shape. Smoother vehicle shapes have already reduced drag significantly, but further reductions of 20-30% are possible.

Rolling Resistance - 4.2%

Rolling resistance is a measure of the force necessary to move the tire forward and is directly proportional to the weight of the load supported by the tire. A variety of new technologies can be used to reduce rolling resistance, including improved tire tread and shoulder designs and materials used in the tire belt and traction surfaces. For passenger cars, a 5-7% reduction in rolling resistance increases fuel efficiently by 1%.

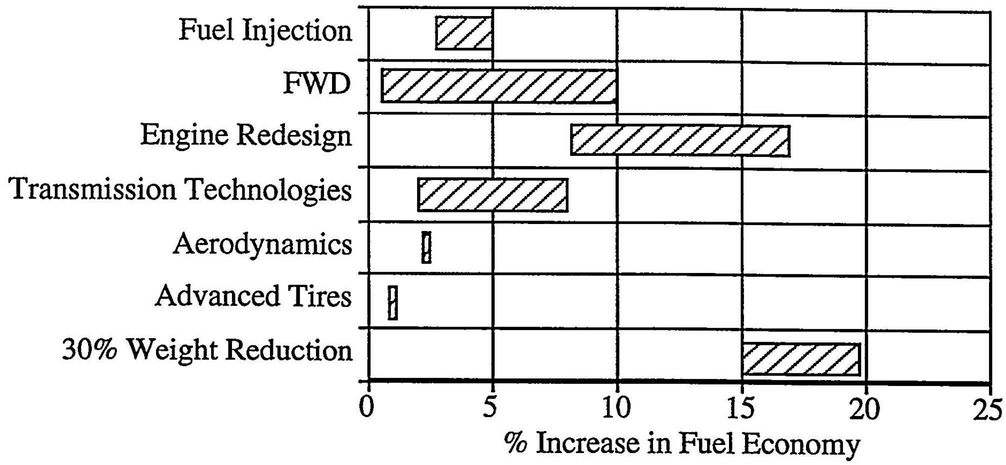

Figure 4. Vehicle Fuel Economy Improvement Potential for Various Technologies (Stodolsky, 1995)

From the inefficiency flow diagram, one can deduce that saving energy at the wheels offers immensely amplified savings at the fuel tank. Figure 4 depicts fuel economy improvement potentials for implementation of various subsystem technologies. It is clear that a 30% weight reduction, a mid-century target assumed by many in the automotive industry, will yield the greatest improvements in fuel economy and associated reductions in emissions.

Vehicle Mass Distribution

Several studies have examined the distribution of mass within typical vehicles. Stodolsky (1995) showed a mass distribution in a passenger car (according to component groups) with the body, about 43% of the total vehicle mass, is the single heaviest group; followed by the powertrain and chassis, in almost equal proportions, at 27% and 26%, respectively. More recently, Bandivadekar et al (2008) found that within the body group, the unit-body, or body-in-white (BIW), is the single largest component, with about 28% of the total vehicle mass (Figure 5). Further analysis showed that the engine is the single heaviest component within the powertrain group, with roughly half the group weight, or about 14% of total vehicle mass, while the transmission represents about 5% of total vehicle mass. The chassis group is not dominated by any single component; the wheels and tires are usually the single heaviest system, but represent only around 6% of the entire vehicle mass (Stodolsky, 1995).

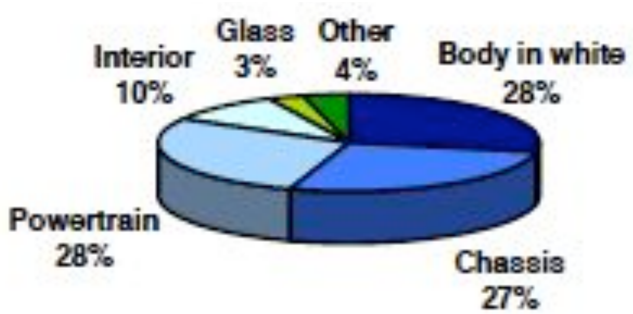

Figure 5. Vehicle mass distribution by subsystem (Bandivadekar, 2008)

Mass Decompounding Concept

Intuitively, vehicle design engineers know that an unplanned mass increase in a component during vehicle design has a ripple effect throughout the vehicle; other components need to be made larger, which increases vehicle mass even more. Malin (2007) writes:

> *The phrase mass begets mass describes this phenomenon. A more encouraging view of this behavior is considering a reduction in the mass of a component enabled by a new technology resulting in a greater mass saving for the overall vehicle. These secondary mass changes can be considerable – estimated at an additional 0.7 to 1.8 times the initial primary-mass change.*

The compounding effect of mass savings on each subsystem in the vehicle - mass decompounding - is a key to efficient vehicle design. A lightweight body requires lighter chassis components and a smaller powertrain, further reducing mass in a "beneficial mass spiral" (Malin, 2007). Optimization and iteration of mass decompounding often will reveal opportunities to make components smaller; and in some cases to eliminate them completely.

For example, a lightweight vehicle body will result in smaller brakes, with reduced or even eliminated power braking booster componentry. Accelerating lighter vehicles cuts drive system output, reducing driveline-support structural needs. Smaller, reduced power drive components require smaller cooling systems with less coolant mass and smaller air inlets, reducing aerodynamic drag losses and thus reducing needed drivesystem energy and power, making those components even smaller and lighter.

New drive/powertrain technologies also benefit from mass decompounding: a lightweight series hybrid may not need transmission, clutch, flywheel, axles, differentials, driveshaft, universal joints, starter, and alternator, but it will need some new components such as drivemotor(s), power electronics, and electrical storage; all of which can be made smaller if the vehicle mass is reduced. Smaller acceleration and gradability loads may also allow a fixed-ratio reduction gear for the traction motor(s), eliminating any multispeed transmission. The reduced requirements may even displace all gearing with low-speed, high-torque motors. Generally speaking, any powertrain will be smaller, lighter and cheaper in a lightweight and energy-efficient vehicle body than in a heavy and inefficient one. Lovins (2004) states, “this can permit the adoption of the most advanced, clean, and efficient powerplants earlier than if they are sized to propel heavy, inefficient platforms.”

The typical question then asked is when lightweighting the vehicle’s structure, thoroughly examined by Malen (2007), becomes:

> *Given a balanced vehicle under design, a primary mass change now occurs during design. What is the final vehicle mass after resizing subsystems?*

Malen presents a means to quantify the secondary mass change with a mass-compounding model. In this model, an influence coefficient, γ_I, is assigned each subsystem (denoted by i). The influence coefficient is defined as, “the change in the subsystem mass when gross vehicle mass undergoes a unit change.” The final change in vehicle mass depends on the sum of coefficients for all subsystems that may undergo resizing. Malen defines this as the vehicle mass influence coefficient, γ_V.

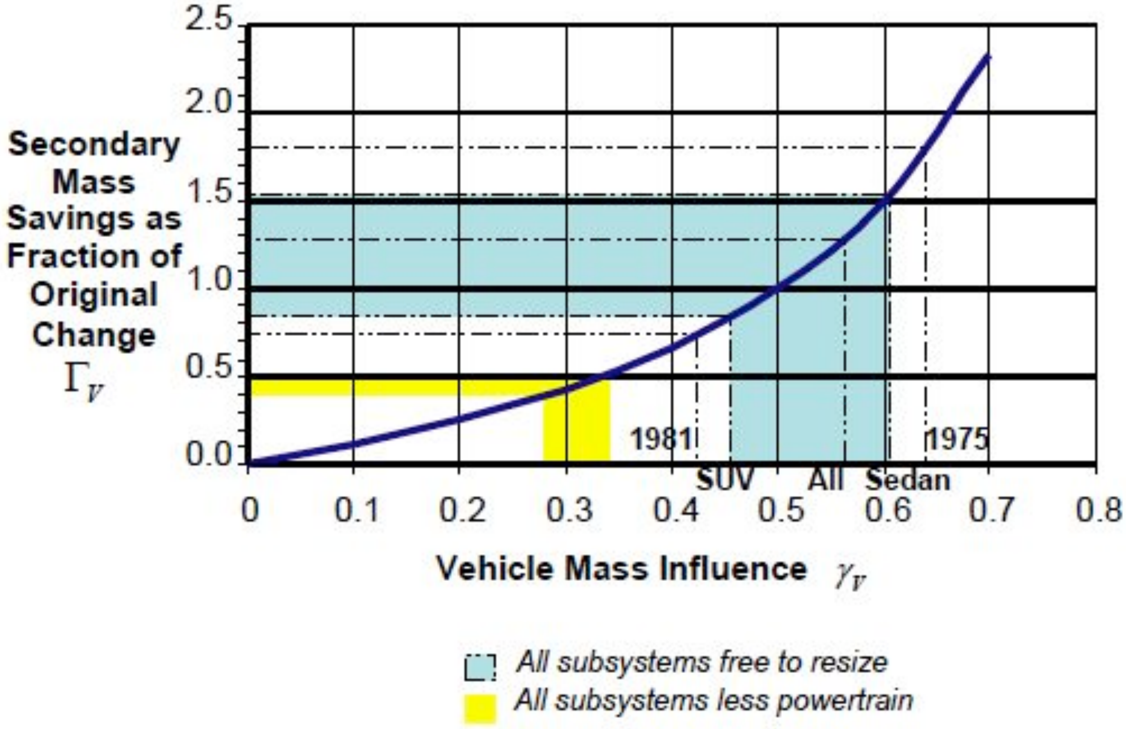

Figure 6. Secondary Mass Savings (Malen, 2007)

As Figure 6 shows, when all subsystems can be resized, the secondary mass savings is from 0.8 to 1.5 kg/kg. When the powertrain has been fixed and is not available for resizing, the secondary mass savings is from 0.4 to 0.5 kg/kg (Malen, 2007).

Other studies, such as given by Moore (1996), describe mass decompounding as "nonlinear, discontinuous, complex, and inadequately captured by automakers' rule-of-thumb ~1.5x multiplier ." All agree, that for a given payload capacity, the primary and secondary units of mass saved converge over recursive reoptimizations, and more rapidly as payload mass becomes a relatively larger factor than curb mass. Again, this does not apply as the case of reaching the threshold at which mass reduction allows an economical series hybrid-electric drivesystem with fewer mechanical parts and smaller components, resulting in greater improvements to overall vehicle efficiency.

If advanced lightweighting material substitution was used to cut BIW mass by 50% and other components downsized accordingly, with no recursions, 40% curb mass reduction might be challenging. However, recursive optimization uncovers many linked opportunities for mass and cost savings. Moore (1996) states, "If substitutions are applied to all components, which in turn require less structure, and the process is repeated several times, 45–55+% curb mass reduction is achievable."

Vehicle Structural Materials: Conventional

A number of different materials are used in manufacturing passenger cars. Some are selected to perform highly specialized functions, while others, like steel, cast iron and aluminum, usually perform a more general "structural" function. The estimated material content in a typical American-made passenger car is shown in Table 1.

Nearly three-quarters of an average vehicle's weight is incorporated in its powertrain, chassis, and body; the bulk of this is made of ferrous metals (Stodolsky, 1995). Other structural materials found in an average automobile, used to a much smaller extent, include aluminum, plastics or composites. Figure 7 shows how the use of aluminum and high-strength steel (HSS) as a percentage of total vehicle mass has been increasing over the past two decades, while the use of iron and mild steel has been declining.

	Mass (lb)	%
Mild steel	1,376	43.7
HSLA steel	259	8.2
Stainless steel	43.5	1.4
Other steels	48	1.5
Total steel	1726.5	54.8
Cast iron	411.5	13
Total ferrous	2,138	67.9
Plastics/composites	245	7.8
Aluminum	177	5.6
Rubber	134.5	4.3
Glass	88.5	2.8
Copper/elec. eq.	43.5	1.4
Powder metal	26	.8
Lead	24	.8
Zinc (die casting)	16	.5
Other materials	68.5	2.2
Fluids/lubricants	188.5	6
Total	3,149.5	100

Table 1. Material Content in Typical Passenger Car (Stodolsky, 1995)

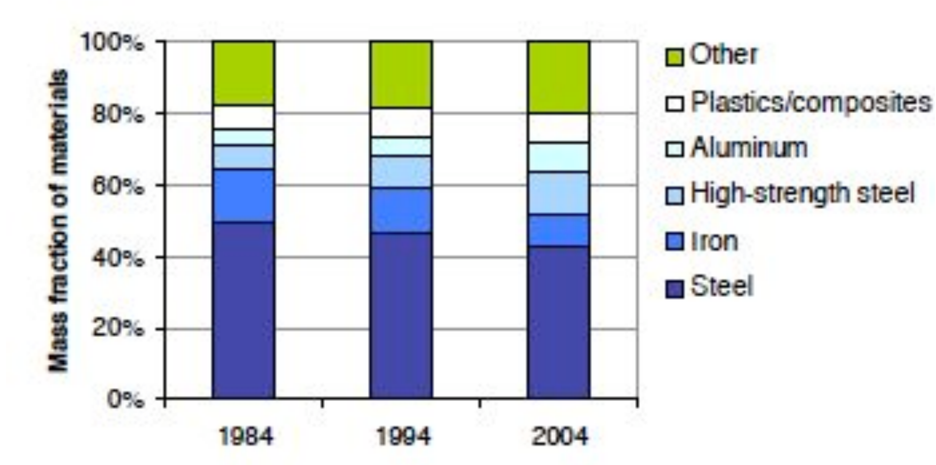

Figure 7. Material composition of the average automobile in the U.S. (Bandivadekar, 2008)

Stodolsky (1995) concludes that 19% of the mass of the car can be classified as special-function materials that would be very difficult to replace with alternate, lightweight materials. He writes, "The potential for significant vehicle weight reduction clearly involves replacement of the 68% of the mass constituted by ferrous materials. The single largest opportunity for lightweight material substitution lies with the BIW, which is made primarily from mild steel."

Vehicle Structural Materials: Advanced

There are three main structural advanced material group candidates: advanced high strength ferrous alloys, light metals (aluminum, magnesium, and titanium) and composites, including polymers. The relevant properties of these materials are summarized in Table 2 and Figure 8 below, and are discussed in turn.

Material	Density, g/cm^3 (relative)	Yield strength, MPa	Tensile strength, MPa	Elastic modulus, GPa	Relative cost per part [Powers 2000]
Mild steel	7.86 (1.00)	200	300	200	1.0
High strength steel (A606)	7.87 (1.00)	345	483	205	1.0-1.5
Iron (D4018)	7.10 (0.90)	276	414	166	-
Aluminum (AA6111)	2.71 (0.34)	275	295	70	1.3-2.0
Magnesium (AM50)	1.77 (0.23)	124	228	45	1.5-2.5
Composites - Carbon fiber - Glass fiber	1.57 (0.20)	Flexural: 200	810	190	2.0-10.0

Table 2. Properties and prices of alternative lightweight automotive materials (Bandivadekar, 2008)

A recent US D.O.E. (2006) comparison for the use of engineering materials shows that steel is the most widely used material, with 725 million tons used each year. Aluminum and stainless steel are used at a rate of 20 million tons, 14.5 million tons, respectively. Titanium is much less widely used at 0.04 million tons per year.

Although advanced lightweighting materials are sometimes considered “high strength alloys,” strength is only one factor in evaluating a particular material substitution. A better measure is the “specific strength” – the material’s ultimate tensile strength normalized by its density. Additionally, many automotive components have structural stiffness specifications as the primary design requirement; in this case the proper parameter to consider is a material’s “specific stiffness” – the material’s elastic modulus normalized by its density. Figure 9 plots various materials in terms of their specific stiffness vs. specific strengths. Interestingly enough, most engineering alloys in widespread use (steels, aluminum, magnesium, titanium) have nearly the same specific stiffness. (Figure 10)

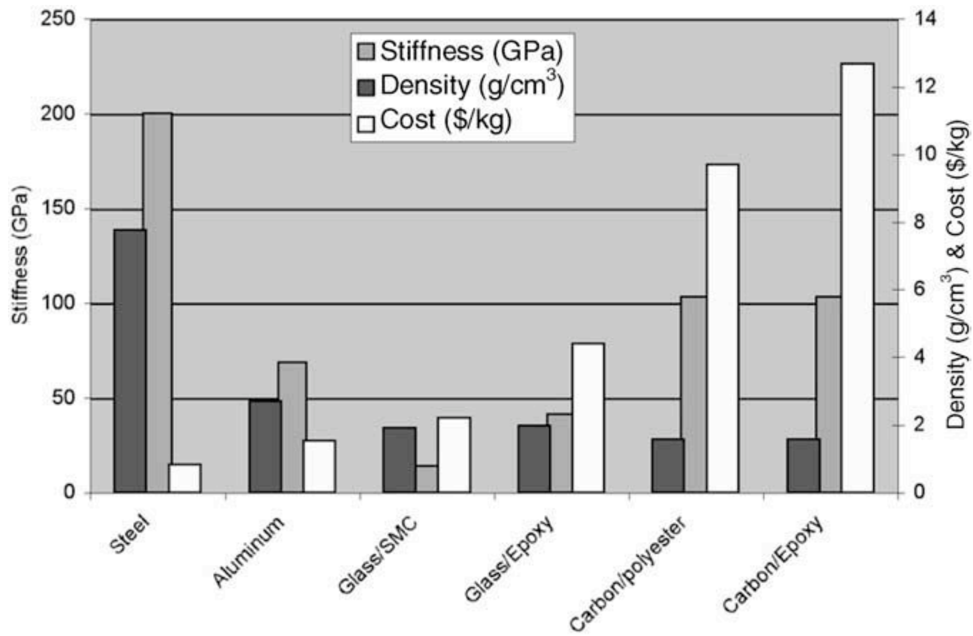

Figure 8. Relative Materials Properties and Costs (Lovins, 2004)

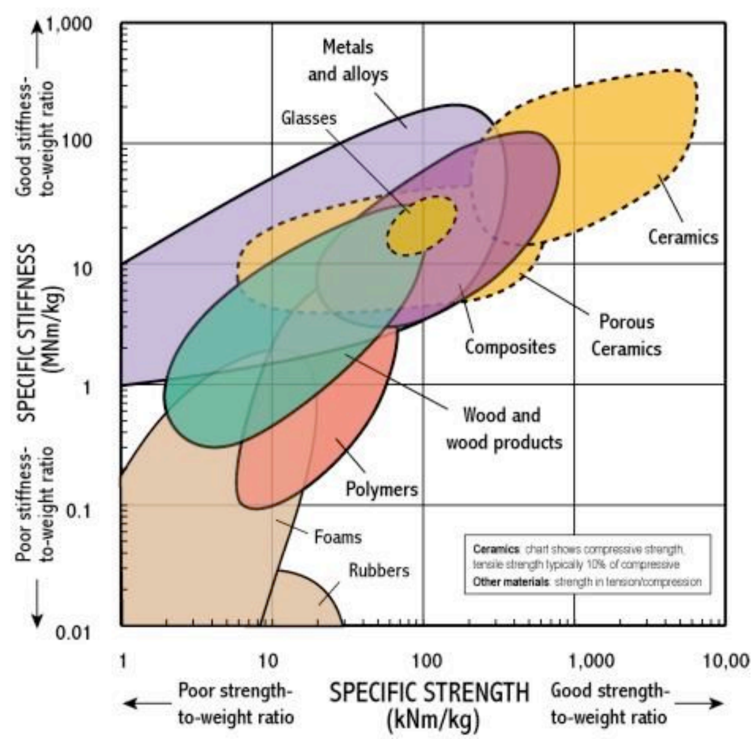

Figure 9. Specific Stiffness/Strength Plot for various materials
(Source: http://www-materials.eng.cam.ac.uk/mpsite/)

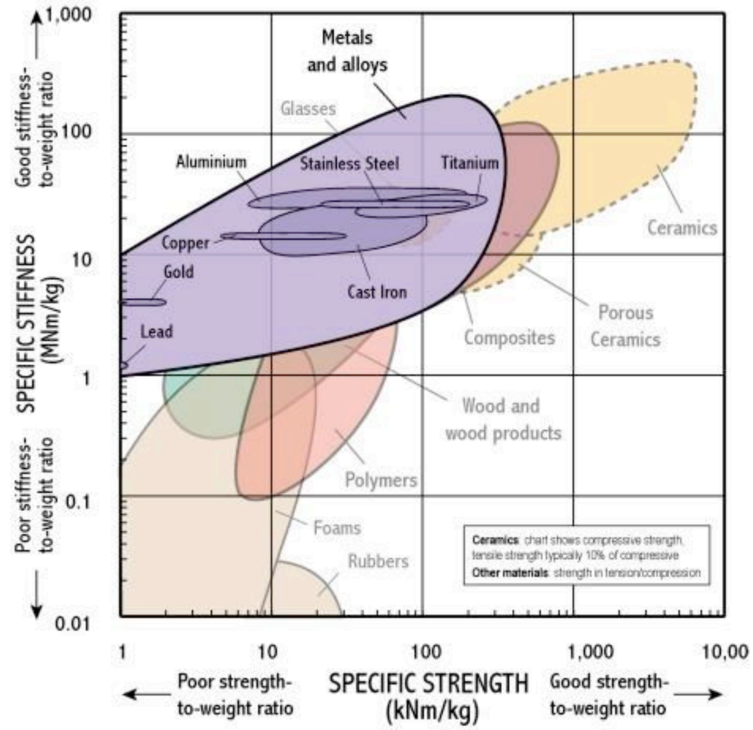

Figure 10. Specific Stiffness/Strength Plot for engineering alloys
(Source: http://www-materials.eng.cam.ac.uk/mpsite/)

Advanced Ferrous Alloys

According to the International Iron and Steel Institute (2006), automotive steels can be classified in several different ways. Common designations include low-strength steels (interstitial-free and mild steels); conventional HSS (carbon-manganese, bake hardenable, high-strength interstitial-free, and high-strength, low-alloy steels); and newer types of Advanced High Strength Steels (AHSS), typically classified by microstructure at room temperature. These AHSS include dual phase, transformation-induced plasticity, complex phase, and martensitic steels. Additional AHSS for the automotive market include ferritic-bainitic, twinning-induced plasticity, nano, hot-formed, and post-forming heat-treated steels.

A second classification method important to part designers is strength of the steel, since steel alloys have virtually the same density and elastic modulus throughout strength ranges. One such system defines High-Strength Steels (HSS) as yield strengths from 210 to 550 MPa and tensile strengths from 270–700 MPa, while Ultra/Advanced High

Strength Steels (UHSS or AHSS) steels have yield strengths greater than 550 MPa and tensile strengths greater than 700 MPa. In addition, many steel types have a wide range of grades covering two or more strength ranges.

A third classification method presents various mechanical properties or forming parameters of different steels, such as total elongation, work hardening exponent n, or hole expansion ratio; all measures of formability. As an example, Figure 11 compares total elongation – a property related to formability – for the different metallurgical types of steel.

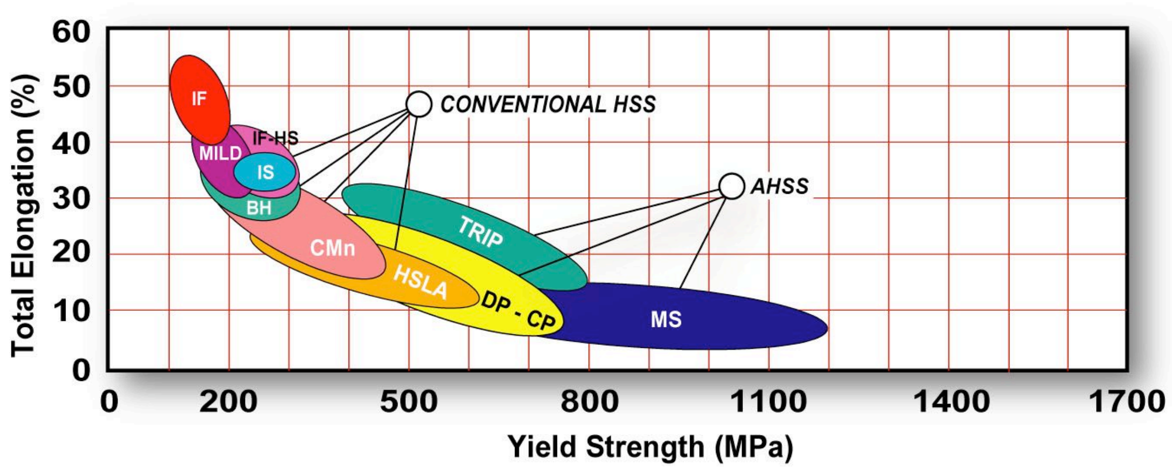

Figure 11. Relationship between yield strength and total elongation (50.8mm gauge length) for various types of steel (r/t) for various AHSS (International Iron and Steel Institute, 2006)

The principal difference between conventional steels, HSS and AHSS is their microstructure. Mild steels are low strength steels with a ferritic microstructure and some strengthening techniques. Drawing Quality (DQ) and Aluminum-Killed Draw Quality (AKDQ) steels are examples and often serve as a reference base because of their widespread application and production volume (Auto/Steel Partnership, 2008).

Conventional HSS are single-phase ferritic steels. AHSS are primarily multi-phase steels, which contain ferrite, martensite, bainite, and/or retained austenite in quantities sufficient to produce desired mechanical properties. Some types have a higher strain hardening capacity resulting in a strength-ductility balance superior to conventional steels. Other types have ultra-high yield and tensile strengths and show a bake-hardening behavior.

Figures 12 and 13 depict typical stress-strain curves for lower-strength dual-phase (DP) and high-strength martensitic (MS) AHSS. Note the tradeoff between ductility and strength, and the variation in energy absorption capabilities (area under stress-strain curve). The former would be more suitable for energy dissipation (crush) applications; the latter would be preferred for intrusion protection (passenger safety cell) applications.

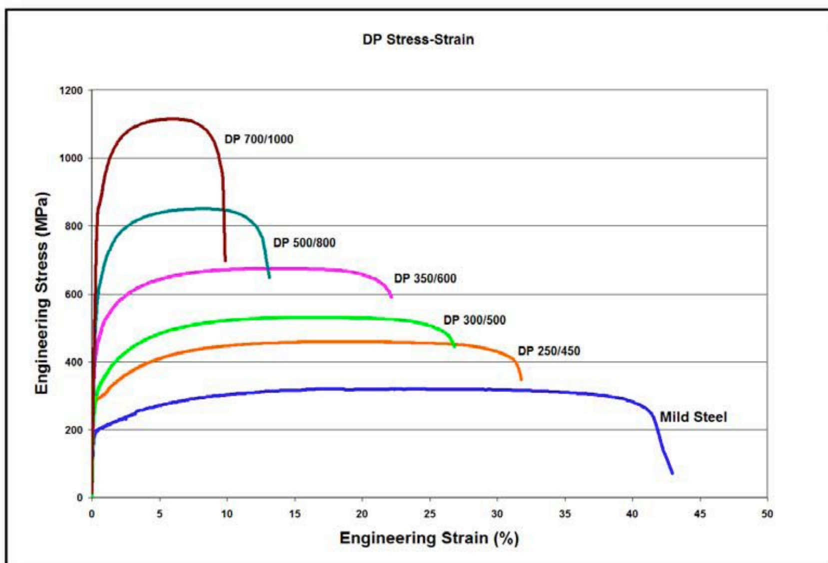

Figure 12. Engineering stress-strain curves for HSS – Dual Phase (DP) steel grades (International Iron and Steel Institute, 2006)

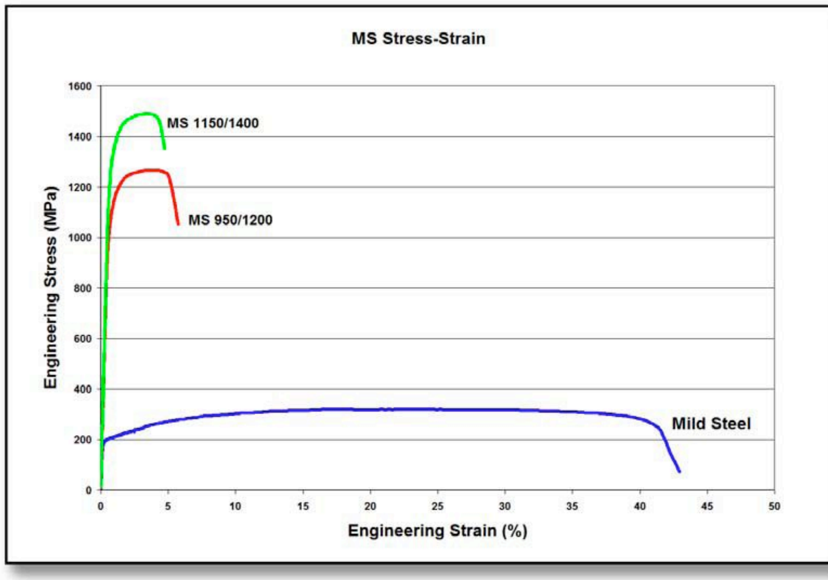

Figure 13. Engineering stress-strain curves for AHSS – Martensitic (MS) steel grades (International Iron and Steel Institute, 2006)

The basic premise in designing with HSS or AHSS is to take advantage of high material strengths relative to conventional steels. The usual result is “down-gauging” a particular part; reducing its wall thickness to save weight while still maintaining functionality and strength. This approach has limitations, and does not work as well on parts that are stiffness-driven, as opposed to strength-driven, simply due to the fact that all steels, mild or AHSS, have nearly identical elastic moduli, density and resulting specific stiffness. Very thin gauges, if not properly implemented, can introduce new failure modes such as buckling and negatively effect noise, vibration and harshness (NVH) ride characteristics.

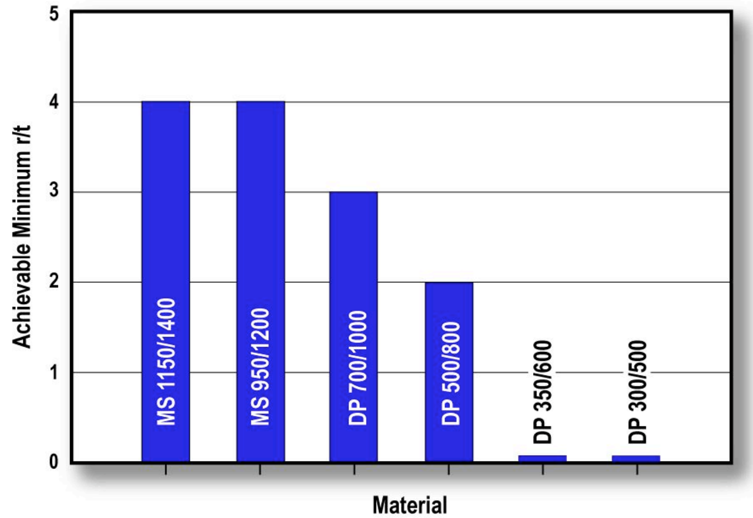

Figure 14. Minimum bend radius (r/t) for various AHSS (Auto/Steel-Partnership, 2008)

Additionally, moving to increasingly stronger materials also limits their formability, and hence, their range of potential weight saving applications. Figure 14 shows forming limitations encountered in bending AHSS.

To combat this problem, alternate AHSS materials and forming methods are employed. (Figure 15) Hot Forming (HF) and Post-Forming Heat-Treatment (PFHT) are two methods successfully used to create optimized part geometries with intricate shapes and no springback issues with very high strength steels (ultimate tensile strengths > 1300 MPa), such as boron-treated steels and martensitic stainless steels.

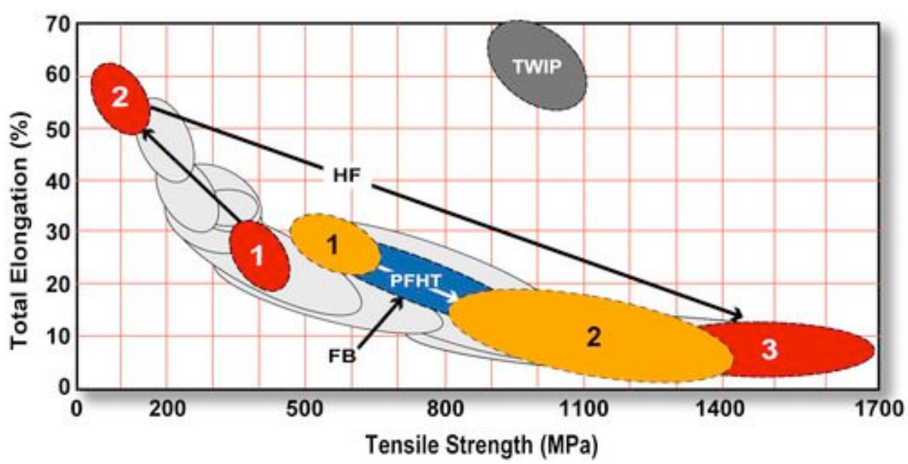

Figure 15. Alternate AHSS processing: Hot Forming (HF) and Post-Forming Heat-Treatment (PFHT). (International Iron and Steel Institute, 2006)

Hot Forming (HF) steel involves press-forming quench hardenable steels at temperatures above the austenitic region (900-950º C). During processing, the three red states identified by Figure 15 with different mechanical properties are important: (International Iron and Steel Institute, 2006)

1. *Tensile strengths up to 600 MPa at room temperature must be considered for the design of blanking dies.*
2. *High elongations (more than 50%) and low strengths at deformation temperatures allow forming of complex shapes. A special coating based on aluminum and silicon is recommended to avoid surface oxidation of the product after forming.*
3. *Following forming, strengths above 1300 MPa are achieved after quenching in the die.*

Typical cycle time is much longer than conventional stamping: 20 to 30 seconds for each press cycle. However, several parts can be stamped at the same time in shared dies so that 2 or more parts can be obtained per cycle. Hot-forming boron-treated steels are most commonly used for safety and structural parts.

Post-Forming Heat-Treatment (PFHT) is a general method to develop a high strength part by forming in the annealed (soft) condition and then subjecting the part to a hardening heat-treatment. The states, identified in blue on Figure 15: (International Iron and Steel Institute, 2006)

1. *The stamping is formed at a lower strength; the alloy has sufficient ductility in its annealed condition.*
2. *The part is then raised to a much higher strength by heat-treatment, involving a hardening quench & temper (Q+T) heat-treatment process.*

The main benefit of PFHT technology is that is allows for forming of complex geometries; at the same time creating a high strength structure after hardening. The major issue holding back widespread implementation of PFHT typically has been maintaining part geometry during and after the heat treatment process. AHSS which posses air-hardening characteristics are much less prone to distortion during the hardening cycle. Air-hardening alloys are those that obtain a martensitic microstructure even when quenching with relatively slow cooling rates, similar to cooling in still air. Chemistries allow in-part strengths between 900 and 1,400 MPa tensile strength, from alloys that feature very good forming properties in the soft-state (deep-drawing capabilities) and high strength after heat treatment. Excellent hardenability and is achieved by adding, in addition to carbon and manganese, other alloying elements such as chrome, molybdenum, vanadium, boron, and titanium (Auto/Steel Partnership, 2008).

In either case, special processes must be taken into account when finishing the product (no additional forming, special cutting and trimming devices, etc.) due to the hardened nature of the part.

The American Iron and Steel Institute (AISI) claims that with a holistic, i.e. recursive optimization, approach to design, vehicle curb mass reductions up to 40% can be achieved with AHSS (US D.O.E., 2006).

Aluminum Alloys

Aluminum (Al) alloys have several properties that are attractive to auto designers. Its density is one-third that of steel, certain Al alloys exist with excellent strength, and other alloys exhibit excellent formability. It is easy to machine, cast and fabricate, and is fairly corrosion-resistant. However, Al alloys perform poorly in fatigue, and are more difficult to weld than conventional steel alloys.

Only nine percent of the mass of the average automobile in the United States is aluminum (Bandivadekar, 2008). Most of this is in the form of aluminum castings and used mainly in the engine, wheels, transmission, and driveline. Figure 16 depicts mechanical properties of various Al casting alloys. Casting is ideal, not only due to the lower melting point of Al and subsequent ease of processing, but also for the potential of part-integration and further mass reduction, if the designer can successfully integrate a number of individual parts into a single casting.

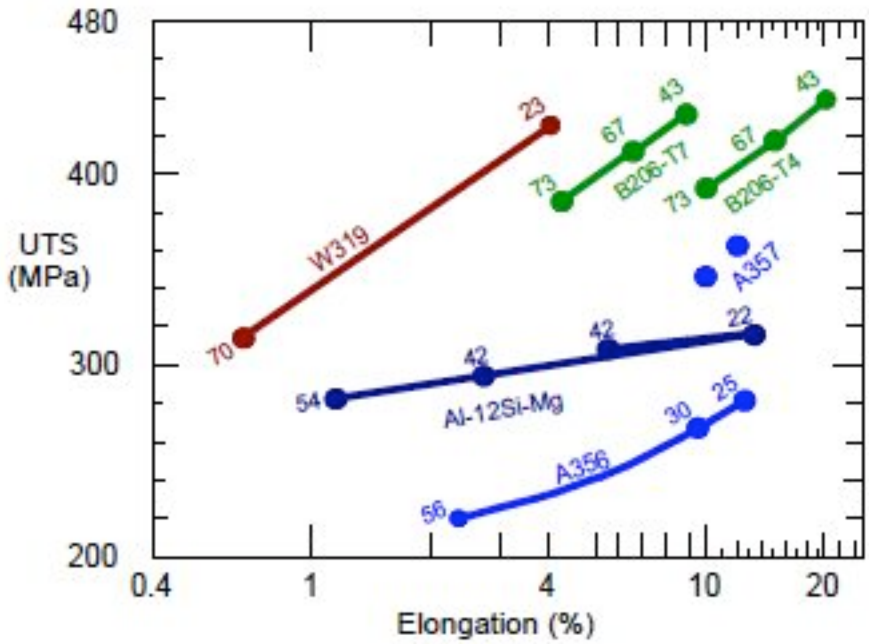

Figure 16. Range of mechanical properties in Al casting alloys (US D.O.E, 2007)

Stamped-sheet aluminum body panels are not as prevalent; sheet Al is more difficult to form than steel and has to be handled with care to prevent scratches because it is softer. An article on vehicle mass reduction by Clarke (2005) quotes John Sellors, a Materials and Processes Engineer in Vehicle Engineering at Lotus:

> *"Aluminum is creeping into mainstream production cars in terms of pressed panels like closures, hoods and tailgates. There is still quite a lot of learning to be done in terms of the use of aluminum from a forming and press stamping point of view. The OEMs have a lot of experience in steel, but aluminum press forming is very different. So rather than take a massive risk and jump straight in with the whole monocoque most OEMs tend to go through the learning process with some lower risk of panels like hood outers."*

Studies project that Al alloy use will reach 144 kg per vehicle in 2010 (Bandivadekar, 2008). Currently, large-scale use is restricted to the high-value end of the market. Models such as the Audi A8, Jaguar XJ and XK, Corvette Z06, in addition to niche vehicles like Aston Martin, Lamborghini and Ferrari make intensive use of Al alloys; mostly for improved power-to-weight ratios on their high performance vehicles (Clarke, 2006).

Ford Motor Company's 199-kg Taurus AIV (Aluminum Intensive Vehicle) demonstration BIW is 47% lighter than the standard Taurus BIW. The aluminum BIW for Volvo's five-seat hybrid ECC (Environmental Concept Car) also weighs ~200 kg, has sufficient strength to carry 350 kg of batteries plus payload, and includes extensive provisions for crashworthiness (U.S. DOE, 2006).

BIW mass reductions up to 55% using aluminum may be technically feasible for high-volume production, although the economics of doing so are still uncertain due to the increased material cost (U.S. DOE, 2006).

Magnesium Alloys

Magnesium (Mg) alloys are the one of the lightest metallic structural materials, 30% less dense than aluminum and 75% lighter than steel. It is also easier to manufacture and cast, having a lower latent heat (it solidifies faster, and die life is extended), and being easier to machine. However, it has a lower ultimate tensile strength, fatigue strength, modulus, and hardness than Al. Additionally, Mg alloys are strain rate and temperature sensitive so press forming cycle times are considerably longer than with Al alloys (Clarke, 2006).

The world's automakers already use Mg alloys for individual components. Diecast Mg alloys have historically been used where a high level of part integration is feasible, such as for instrument panel beams. Other applications include knee bolsters, seat frames, intake manifolds, and valve covers. Currently, Mg parts are concentrated in well-protected regions of the car that are not exposed to corrosive environments. Corrosion protection of Mg becomes a serious issue in exposed applications, for example, body and chassis structures. For such parts, manufacturers can consider proprietary anti-corrosion pre-treatments available for Mg alloys, which transform the surface of light alloys into a dense, hard ceramic with outstanding resistance to corrosion and wear (Clarke, 2006).

Newer applications include Mg/Al composite engine blocks. According to Clarke (2006), BMW's six-cylinder Mg/Al crankcase is the lightest used in large-scale production, weighing 57% of a comparable grey-cast iron block; the weight advantage in comparison to an all Al alloy crankcase is 24%. Novel structural uses of Mg include the Corvette Z06 Mg engine cradle, cast as a single-piece component using a newly developed high-temperature Magnesium Alloy: AE44. The 10.85kg engine cradle replaces large multi-piece assemblies and provides a 35% weight saving versus the original Al design (Clarke, 2006).

	Condition	Grain size (μ m)	RMT		400°C	
			Elongation (%)	UTS (MPa)	Elongation (%)	UTS (MPa)
AZ31	H24	~10	12.2	294.5	37.9	20.5
ARB1	64 layers	Min. 1	9.0	234.0	137.9	22.6
ARB2	Al'-Mg'-'Al	Mg-5	15.2	199.5	64.8	29.5
ARB3	AZ31-70%	5	21.8	288.0	126.9	21.5

Table 3. Mechanical Properties of Wrought Mg Alloys (US D.O.E., 2006)

In recent years, the abundance of Mg in China has had the effect of lowering the raw material cost, at times lower than that of Al (Clarke, 2008). However, new processing methods and Mg alloys are needed before it can become economically and technologically feasible as a major automotive structural material (Nyberg, 2008). Table 3 lists mechanical properties of wrought Mg alloys, typically considered for stamped applications. Note the brittle nature (low elongation) at room temperatures; most forming of sheet Mg alloys is done “warm” to increase formability. Conversely, this increased formability at high temperatures results in low creep-resistance and stress rupture failure at higher temperatures for typical Mg alloys.

Per-vehicle Mg alloy content is expected to grow from 3.5 kg today to 7.3 kg in 2010. The U.S. Automotive Materials Partnership (USAMP) has forecasted a very ambitious goal of 160 kg/vehicle by 2020 (Bandivadekar, 2008).

Titanium Alloys

Although titanium (Ti) alloys possess an attractive set of properties – including high specific strength, corrosion resistance, toughness and specific stiffness – their cost limits application to selected markets. The aircraft industry is currently the single largest market for Ti alloy products due to the exceptional strength-to-weight ratio, elevated temperature performance and corrosion resistance. However, this strong dependence of Ti on the aerospace industry has caused Ti production to be very cyclic. Currently, Ti alloy sheet costs are around \$40–50/lb, and lead times for product delivery from time of order can be as long as 18 months (US D.O.E., 2006).

Many automotive systems would benefit from the use of Ti alloy products. Ti automotive exhaust systems could save as much as 50% of their current mass (US D.O.E., 2006). Ti valves and valve springs, connecting rods, suspension springs, wheels, drive shafts, underbody panels, side impact bars, and half shafts are just some of the automotive applications that could benefit from the use of Ti.

Technical problems preventing the integration of Ti, apart from the cost of manufacturing, include wear resistance, a lower modulus than steel, welding and machining difficulties. Coatings, reinforcements, and compositing can improve wear resistance (US D.O.E., 2006). The machining difficulties can be reduced by the production of near-net-shape parts through powder metallurgy or other methods. The major problem is that Ti costs substantially more than competing materials.

Although the raw cost of Ti ore is significantly more than that of other materials, the difference in the cost of sheet, plate, and most other Ti alloy product forms is largely due to the cost of secondary processing or milling operations (Figure 17).

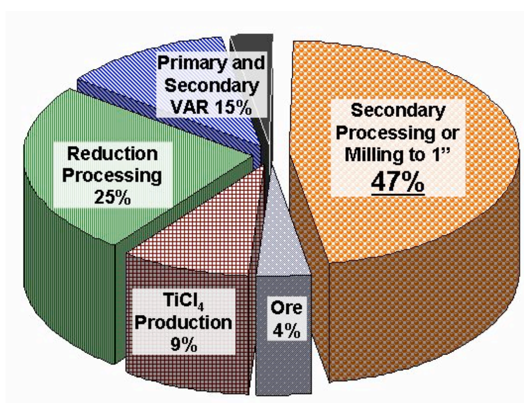

Figure 17. Breakdown of cost in the production of 1in. CP Ti plate (US D.O.E., 2006)

Batch processing methods such as Vacuum Arc Reduction (VAR) are inherently costly, but needed to produce refined Ti alloys. Additionally, thinner plate and sheet gauge sections increase the production costs due to additional batch-type heat-treating and rolling steps involved, increasing the amount of production waste, and the percentage of total production costs. Processing of Ti from ingot to 1-in.plate accounts for 47% of the total cost of the material (US D.O.E., 2006).

Composites

Composites offer high specific material strength and stiffness, along with very high fatigue resistance, allowing for significantly reduced mass while maintaining or even improving component strength and durability and vehicle stiffness. The mechanical properties and degree of isotropy of polymer composites are controllable over a wide range, depending on reinforcing fiber orientation and composition.

While 7.5% of total vehicle mass currently is composed of plastic and composite materials, the applications are typically not for the primary vehicle structure (US D.O.E., 2007). Currently, these low-strength composite forms are chosen for ease of processing and moderate mass reductions.

The most common composites in use today are glass fiber reinforced thermoplastic polypropylene, which is applied to rear hatches, roofs, door inner structures, door surrounds, and other trim and interior components. Other types include glass mat thermoplastics, sheet-molding compounds (SMC) made of glass fiber reinforced thermoset polyester, and glass fiber reinforced thermoset vinyl ester. For instance, SMC can be stamped into shape, with much lower capital costs relative to steel, and lower density. Together, these attributes result in overall cost and weight savings. However, due to the low-performance fibers used, random orientation of the fibers, and low fiber volume fraction, the structural performance and degree of lightweighting offered by SMC and many of its current rival material systems are only moderate. (US D.O.E., 2007, Figure 18)

Carbon fiber reinforced polymer (CFRP) composites are more expensive and less popular than their glass fiber-reinforced cousins, although they offer significant strength and weight-saving benefits.

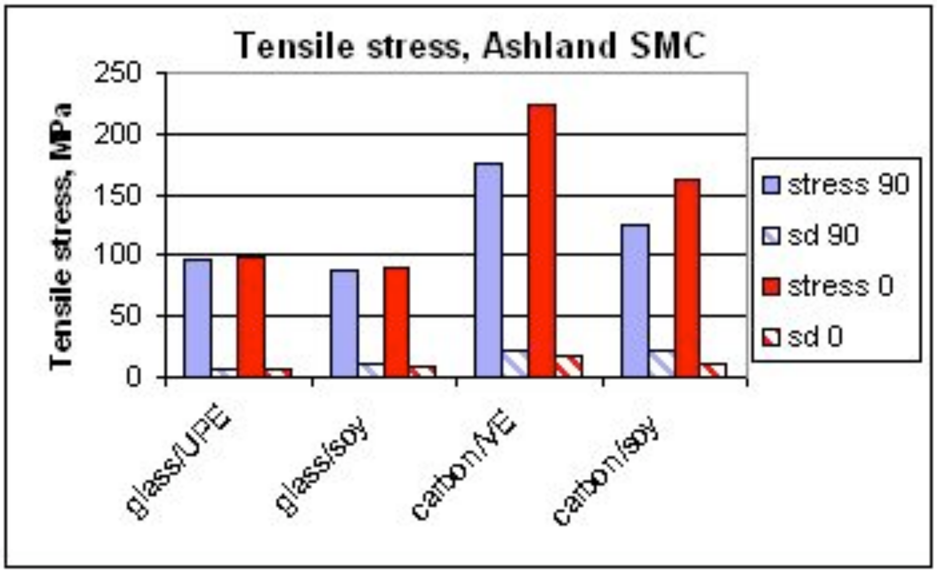

Figure 18. Tensile Strength of Typical Automotive Composites, Sheet Molding Compounds (SMC) Petroleum vs. Soy Resins (US D.O.E., 2007)

Advanced CFRP composites are the most logical replacement for steel in vehicle structures where significant weight reduction is desired. Currently, GM's Corvette Z06 features carbon-fiber front fenders resulting in a 6kg reduction of vehicle mass (Clarke, 2008). Industry analysis shows potential for 60–67% BIW mass reduction using CFRP (Lovins, 2004).

However, as Bandivadekar (2008) states, "The two most widely cited obstacles to the use of carbon composites in automotive structures are the high cost of the raw materials (~$11–22/kg vs. ~$1.3/kg for steel) and the high labor required to produce advanced composite parts."

Lovins (2004) promotes CFRP in RMI's "Hypercar" design, and states that specific crash-energy absorption of CFRP can be 2-5 times that of steel. Lovins adds that molding characteristics of composites can provide greater styling flexibility and reduced assembly steps, finish processes, and tooling through parts consolidation and lay-in-the-mold finish coatings, potentially eliminating CFRP material cost penalties.

However, these materials do face manufacturing challenges. Composite parts for structural applications typically suffer from high per-unit costs and slow processing cycle times, which confine their use to premium ultra-low volume products (Clarke, 2005). Other technical challenges of CFRP include the lack of infrastructure needed to deliver large quantities of materials and the difficulty in recycling of composites at the vehicle's end of life.

Implementation challenges

Manufacturability

Implementing advanced materials pose new challenges in manufacturing. Conventional automotive steel forming plants and fabrication processes are not adequate even for some AHSS, much less for Al, Mg, Ti and composites (International Iron and Steel Institute, 2006).

In the case of AHSS, emphasis is being placed on determining specific needs of stamping, highlighting critical forming modes, and identifying essential mechanical properties. The interaction of all inputs to the forming system means the resulting higher loads and energy needs of advanced materials also place new requirements on press capacity, tool construction and protection, lubricant capabilities, process design, and maintenance.

New tooling, processing equipment and technologies are needed for high-volume cost effective production of non-conventional materials, particularly composites.

Joining/Weldability

Advanced lightweighting alloys pose difficulties related to joining and fastening to other structures in the vehicle. While AHSS can be welded to conventional steels, some additional precautions have to be taken during welding for a successful joint. The as-received microstructure will be changed while welding AHSS, negatively impacting the desired AHSS mechanical properties. The higher the heat input, the greater the effect on the microstructure. With higher strength grades of AHSS, fast cooling rates after welding increases the tendency to form martensite and/or bainite microstructures in the weld metal and in the heat-affected-zone (International Iron and Steel Institute, 2006). These areas can be prone to brittle failure in the field, unless additional processing steps are taken.

Welding Al, a better thermal and electrical conductor than steel, requires nearly five times the energy of steel, thus specially modified robots and power supplies are required (Clarke, 2005). Additional concerns arise regarding durability of aluminum spot and seam welds; hence many manufacturers are more likely to use labor-intensive adhesive bonding and mechanical joining methods.

Magnesium parts lend themselves to bolt-on or bonded-on applications; additional isolation precautions are necessary to avoid potentially severe galvanic corrosion. Titanium alloys are weldable; but considered best left for aerospace-certified welders due to their high reactivity with oxygen and risk of weld contamination. Composites are similarly disruptive to present welding-joining process flows and must be integrated to the vehicle structure with mechanical or adhesive means.

Vehicle Performance

Low-mass vehicle dynamics are improved in each aspect: handling, maneuverability, tire adhesion, and braking (Malin, 2007). Design for safety, utilizing lightweight materials vs. conventional materials, does not preclude crashworthiness. Light vehicles can surpass the safety of today's cars in many types of collisions using proven technologies for energy absorption, force-limiting occupant restraints, and rigid passenger-compartment design.

Consumer perception may play an even bigger role in lightweight material implementation. As Moore (1996) writes, "To avoid rejection by consumers, light vehicles should provide at least equivalent safety when colliding head-on with vehicles of average or higher mass at the time of introduction. This may require absorption of several times the static fixed-barrier crash energy in a collision with a vehicle weighing twice as much."

Costs

When alternative materials are used to perform lightweighting, studies have found that on average, weight reduction would cost $2 to $3.50 per kg of weight saved (Bandivadekar, 2008).

To get a sense of the potential applications of lightweight materials in vehicles and their corresponding manufacturing costs, results from different case studies, most examining lightweighting the BIW, available in the literature have been summarized by Bandivadekar (2008) and are presented in Table 4.

The point at which mass reduction minimizes vehicle cost and complexity should be determined before the design is finalized with particular structural materials and component choices (Malen, 2007). Ultimately, these new materials technologies are expected to increase costs, meaning that price increases will be passed on to consumers. However, the impact of such vehicle sales price increases should be somewhat mitigated by the potential savings in fuel costs over the vehicle's operating lifespan.

Lightweight vehicle / component	Incremental OEM cost[45]	Weight reduction	US$ per kg reduction	Volume per yr	Source
General lightweight vehicle	-	-	2.20 to 3.70	-	NRC 2002
High strength steel (HSS)-intensive					
Front end	-$13	11 kg	-1.20	-	Roth 2006
SUV frame	-	(-23%)	0.68	220,000	Altair 2003
Body-in-white	-$32-52	52-67 kg	-1.00 to -0.47	225,000	Shaw 2002
Aluminum-intensive					
Vehicle	$661[46]	346 kg	1.91	200,000	Stodolsky 1995
Unibody	$537	138 kg	3.88	500,000	Han 1994
Polymer composites-intensive					
Body (glass fiber reinforced)	$400	127 kg	3.16	100,000	Kang 1998
Body (glass fiber-thermoset)	$930	68 kg	13.68	250,000	Dieffenbach 1996
Body (carbon fiber reinforced)	-	-	2.20 to 8.82	-	Das 2001
Body (carbon fiber reinforced)	$900	196 kg	4.59	100,000	Kang 1998
Body (carbon fiber-thermoset)	$728	114 kg	6.39	100,000	Mascarin 1995
Vehicle (carbon fiber)	$2,926	444 kg	6.59	200,000	Stodolsky 1995
Body (carbon fiber-thermoplastic)	$1,140	145 kg	7.86	250,000	Dieffenbach 1996

Table 4. Incremental manufacturing cost compared to conventional steel alternative (Bandivadekar, 2008)

Summary

Advanced engineering materials can play an important role in improving the efficiency of transportation engines and vehicles. Weight reduction targets are frequently set as a means to increase the fuel economy of vehicles, thereby reducing exhaust emissions. By reducing mass of the vehicle's main body and chassis structure, secondary weight and cost savings can be realized by downsizing subsystems through the mass-decompounding effect. In addition, weight reduction has many significant secondary benefits, improving performance and handling dynamics.

Lightweighting materials, including AHSS, aluminum, magnesium and titanium alloys, along with composites have significant potential to reduce BIW mass. With the exception of Ti alloys, Table 5 summarizes the highlights and challenges associated with each material.

Material	Current use	Merits	Challenges
Aluminum	130 kg/vehicle, 80% are cast parts e.g. engine block, wheels	- Can be recycled - Manufacturers familiar with metal forming	- High cost of Al - Stamped sheet is harder to form than steel - Softer and more vulnerable to scratches - Harder to spot weld, uses more labor-intensive adhesive bonding
High-strength steel	180 kg/vehicle, in structural components e.g. pillars, rails, rail reinforcements	Makes use of existing vehicle manufacturing infrastructure; there is OEM support for near-term use	- More expensive at higher volume scale - Lower strength-to-weight ratio compared to other lightweight materials
Magnesium	3.5 kg/vehicle, mostly thin-walled cast parts e.g. instrument panels and cross car beams, knee bolsters, seat frames, intake manifolds, valve covers	Low density, offering good strength-to-weight ratio	- Higher cost of magnesium components - Production of magnesium in sheet and extruded forms
Glass-fiber reinforced polymer composite	Some rear hatches, roofs, door inner structures, door surrounds and brackets for the instrument panel	- Ability to consolidate parts and functions, so less assembly is required - Corrosion resistance - Good damping and NVH control	- Long production cycle time, more expensive at higher volume scale - Cannot be recycled
Carbon-fiber reinforced polymer composite	Some drive shafts, bumpers, roof, beams and internal structures	Highest strength-to-weight ratio, offering significant weight-saving benefit	- As with glass fiber composites - High cost of fibers ($17-22/kg)

Table 5. Summary of alternative lightweight automotive materials (Bandivadekar, 2008)

In the near term, AHSS, Al alloys, and possibly Mg alloys, will likely see more use as they are currently the most cost effective option at large production scales. Ti alloys and composites, which presently cost significantly more, will likely take a smaller role in lightweighting until material and production costs are decreased in the future. Targets of 20-35% weight reduction commonly referenced in the literature and discussed among policy makers are easily possible by 2035 through the use of these advanced materials, at a cost of $2 to $3.50 per kilogram of weight saved in the average vehicle. Mass reductions of this magnitude could alone result in up to 20% reduction in vehicle fuel consumption and associated emissions (Stodolsky, 1995 and Bandivadekar, 2008). Further weight reduction, at a more significant cost, could approach 50% through creative use of lightweight materials, redesign and downsizing.

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