Steel and Iron Technologies for Automotive Lightweighting  

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March 3, 2005

ABSTRACT

Materials and techniques for cutting weight from vehicles are a part of routine automotive engineering practice. Large reductions in weight while maintaining size and enhancing vehicle utility, safety, performance, ride and handling are often thought of as requiring radical changes, such as the all-aluminum bodies or carbon-fiber composites sometimes featured in concept vehicles. While these materials are used selectively today and are likely to see broader application in the future, it is important to be aware of the substantial, near-term opportunities from ongoing refinements in less costly, established materials and design techniques. These available technologies—utilizing engineering plastics and light metals as well as steel and iron—offer ways to cut weight incrementally while maintaining or improving other attributes, and can do so at low cost or even cost savings.

Advanced iron and steel technologies have seen substantial development over the past decade and are regularly incorporated into new designs and redesigns by all automakers. The steel industry and component suppliers are investing heavily in innovation. Examples abound of successful, cost-effective applications of high-strength steels, stainless steel, new formulations of iron, and an associated variety of new design, fabrication, and assembly techniques. Uses include not only vehicle bodies, but also engine, chassis, wheels and many other parts. Applications commonly demonstrate weight reduction plus simultaneous improvements in strength, stiffness, and other structural performance characteristics. Thus, a clear potential exists to affordably make vehicles lighter and safer at the same time.

As is the case for powertrain technology, whether or not lightweight steel technologies yield a net fuel economy improvement (in this case, through net weight reduction), depends on the design objectives and product strategy. Since 1987, weight-saving technology has been continually applied to vehicles even as their overall weight has been increasing due to market forces favoring design priorities other than higher fuel economy.

A significant contribution to higher fuel economy is likely to be achievable at low cost by redirecting a portion of this ongoing progress in lightweight steel technology toward net weight reduction. As seen in the examples provided here, weight savings obtained by broader application of the best practices already demonstrated has a high likelihood of being very cost-effective. This finding belies the impression that weight reduction is relatively costly. In fact, weight reduction opportunities are best viewed as a continuum, offering a cost curve unto themselves that progresses from very low cost (indeed even zero or negative cost) options toward those of higher cost. The recent history of steady advances in materials, design and fabrication technique suggests that such capabilities will continue to expand. Given adequate lead time for re-prioritizing vehicle design, advanced steel technologies can deliver additional cost-effective weight savings for many years to come. Further research is needed to better characterize and quantify this important aspect of fuel economy potential for purposes of policy analysis.
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INTRODUCTION
The relationship between a vehicle's mass (weight) and its fuel economy is well known. Other aspects of performance held constant, a vehicle's mass and its fuel consumption rate have a linear relationship. Although the exact benefits must be estimated through careful modeling, a relationship that holds up well in practice is that the elasticity of fuel economy with respect to mass is -0.66, i.e., a 1% mass reduction yields a 0.66% fuel economy improvement at constant performance (with engine downsized and powertrain re-optimized for constant acceleration and drivability). If engine power is not reduced, the benefits of mass reduction are shared between efficiency and performance, and the elasticity drops to roughly -0.3.

For reasons of both fuel economy and performance, vehicles are designed to mass targets. The desired mass is one of many vehicle parameters targeted as the design process unfolds from its early phases to engineering and the latter stages of product development, prototyping, and production. It is the result of a "negotiation" among the numerous and often conflicting requirements of a new or re-designed vehicle. Important for performance and handling as well as fuel economy, a vehicle's ideal mass is a function of many complex interactions and design decisions that force trade-offs among countless attributes that make a vehicle competitive in the market while being produced on budget. Targets can be modified during the course of product development and may be missed, but they create a set of constraints imposed on the engineering of every vehicle component and system. Similarly, mass targets are developed at the component and systems levels as well, with a similar hierarchy of constraints and trade-offs. From an engineering perspective, excess mass is never desirable. Using improved technologies for mass reduction is an essential part of automotive engineering and always has been. The net effect on the weight of the vehicle is a result of design priorities interacting with the ever-evolving state of the art in available materials technology and technique.

Weight can be reduced through several types of technology improvements: in materials, design technique, fabrication processes, packaging (i.e., making better use of space), as well as the functional efficiency of vehicle systems or components (e.g., more compact gear sets that enable a lighter transmission of equal capability; the numerous refinements that enable higher engine specific power, and so on). Many of these strategies interact: an example given below shows how weight-saving performance enhancements in an engine were achieved using...
improved materials (high-strength steel) as well as new components designs yielding a set of compounding benefits and a more compact, optimized system overall.

This paper focuses on mass reduction through advances in the use of iron and steel (ferrous materials), because they are the dominant material (64% of a typical family vehicle), form the critical elements of structure for the vast majority of vehicles, and are low-cost materials with an extensive experience base and familiarity to the industry. However, competition among suppliers for any given material as well as competition between materials results in ongoing progress toward lighter weight, lower costs, and other improvements in component and structural performance. Thus, progress in steel technologies is matched by progress in use of aluminum and other lightweight metals as well as engineering plastics and composites. Although this paper does not attempt to cover these other materials, they too can offer low-cost ways to reduce mass. While body, chassis, engine and other powertrain components made of ferrous materials comprise the largest part of a vehicle by mass, lightweight steel and iron technologies compete with potential substitutes in all of these applications. This competition implies a much broader set of cost-effective mass reduction opportunities than this paper has attempted to examine.

In fact, weight-saving technique goes into every vehicle design and redesign. As is perhaps better known for the case of powertrain technologies, the resulting efficiency gain can be more than offset by increases in performance. For lightweighting, however, performance has a much more expansive meaning, referring not only to acceleration performance (for which weight minimization is in fact very important), but many other aspects of vehicle and component performance such as strength, stiffness, crashworthiness, handling, ride quality, and noise-vibration-and-harshness ("NVH"). It also includes the addition of capacity and capability without detracting from other attributes. Many of these aspects of functionality could add excessive weight, detracting from overall performance unless weight-saving technology were utilized. In its CAFE analyses, NHTSA has noted the potential combination of weight savings with other benefits achievable in the course of the automotive design process; stating, for example, that "Component redesign is an on-going process to reduce costs and/or weight of components, while improving performance and reliability."4

Nevertheless, because of market pressure for other features without market or other needs for higher fuel economy, potential weight savings are not being realized. In spite of the
increasing use of weight-saving technology at the component level, the average weight of new light trucks in the U.S. market has been rising since 1987 and is up by an estimated 1000 pounds as of 2004.5 This weight gain has been more than offset by increased engine power, so that the acceleration performance of cars and light trucks has risen in spite of weight gain. Acceleration ability, as measured by zero to 60 mph (Z60) time, is roughly proportional to a vehicle's horsepower-to-weight ratio (assuming unchanged gear ratios). For a given level of powertrain technology, a 10% improvement in performance (reduction in Z60 time) results in a roughly 4% loss of fuel economy.6 The combined "fuel economy opportunity cost" impacts of (a) mass efficiency-related technologies (materials and techniques for lightweighting) being applied to enable greater size and other capacity enhancements plus (b) powertrain efficiency-related technologies being applied for acceleration performance and other drivability enhancements is substantial: EPA has estimated that the 2004 new light duty fleet could achieve 20% higher fuel economy if it had the same performance and weight characteristics of the 1987 fleet.7

An instructive background example
Any number of vehicles could be picked to illustrate many of the steel technologies discussed here. An interesting example is the previous (1999–2004) generation of DaimlerChrysler's Jeep Grand Cherokee, the company's flagship midsize SUV and a vehicle that helped spur the 1990s SUV boom after its original introduction in 1992. The vehicle's 1999 redesign featured an improved steel unibody which the company put on display that year. It illustrated several contemporary lightweight steel techniques (discussed later in this paper) and weighed less than the preceding generation even though its overall dimensions increased. Quoting from information that Chrysler Division provided at the time:

For the 1999 Grand Cherokee, we took a holistic approach to its structural design, optimizing each body panel and every bracket. This allowed us to increase the mass-efficiency of the body over the previous generation Grand Cherokee body, while substantially increasing structural stiffness for less noise, vibration and harshness, fewer buzz, squeaks and rattles, and better ride and handling with precise on-center steering feel. The "body-in-white," or basic body shell of the 1999 Grand Cherokee is 50 pounds (23 kg) lighter than the previous-generation model, while its torsional stiffness is increased 20 percent. The upper door frame stiffness is 30 percent higher, while the liftgate opening stiffness is increased by 40 percent.8
Jeep's Cherokee and Grand Cherokee helped pioneer the unibody SUV, which has since seen growing popularity in body styles now known as cross-utilities or sport wagons. Remarking on the lightweighting and other benefits of the 1999 redesign, a company official stated:

And mass matters, not only to make a vehicle more nimble and more efficient but also to make it more compatible with lighter obstacles. With the new Grand Cherokee, we think we found the optimum level between a strong body shell and a more impact-absorbing structure.

Lightweight steel techniques (among other technologies for lightweighting) have an ongoing potential to achieve multiple design objectives, including mass reduction for fuel economy improvement, safety improvements for both crashworthiness and compatibility, and other enhancements in vehicle performance and functionality.

As explained below, this paper cannot provide specific information on the costs of lightweight steel technology. But the Grand Cherokee example is again instructive on the question of cost effectiveness. For a given level of state-of-the-art technology, the underlying engineering costs are largely the same, but the benefits (design outcome) depend on the priority of objectives for the product. In the case of the 1999 Jeep Grand Cherokee, fuel economy was improved 5% over the previous generation vehicle, while size, capacity, and performance were simultaneously enhanced. Arguably, engineering costs would have been somewhat lower if, say, the vehicle's size, capacity, and performance had not increased but the same advances in steel technology were applied.

Thus, there can be little doubt about the cost-effectiveness of improved, weight-saving steel technology as seen in the Grand Cherokee (and throughout the auto market). However, it is important not to confuse engineering cost-effectiveness with the broader issue of marketplace value. The automotive product planning focus on providing marketable features results in designs that use technology improvement largely for purposes other than fuel economy. This phenomenon can mask the fact that, if design priorities were different, the same technology could have delivered higher fuel economy at the same or even lower cost.

**Weight reduction in the NRC CAFE study**
The NRC (2002) CAFE study mentioned vehicle weight reduction among the technologies it assessed, but provided little analysis of it and did not reveal a deep knowledge of the extensive weight-reducing techniques that are an established part of engineering practice. The NRC CAFE
committee lacked consensus on the issue of weight reduction and safety, as evidenced by the pointed dissent given in Appendix A of the 2002 report. Perhaps for this reason, the committee did not delve deeply into technology for weight reduction.

The NRC did list a 5% level of vehicle weight reduction in its emerging technology matrix at a retail price-equivalent (RPE) cost of $210–$350.\textsuperscript{11} For their average baseline light truck with a curb weight of roughly 4200 lbs, the implied cost of weight reduction is $1.00–$1.67 per pound. But weight reduction was omitted from the matrix of production-intent technologies. Such a judgment is curious: the committee defined "production-intent" technologies as those that are "already available, are well known to manufacturers and suppliers, and could be incorporated in vehicles once a decision is reached to use them."\textsuperscript{12} As this review shows, numerous weight-saving steel-based technologies certainly fit this definition: they are well known to the industry and in fact being incorporated routinely. The potential for improved steel technology to reduce vehicle weight cost-effectively has been identified for many years.\textsuperscript{13} Thus, the NRC's handling of technology for weight reduction reflects at best an overly narrow understanding of automotive engineering, of which weight-cutting strategies are part and parcel of nearly every aspect of vehicle and component design: body structure and suspension components, interiors, accessories, and all parts of the powertrain and driveline including wheels and tires. And although steel-based lightweighting is the focus here, it is impossible to examine any recent vehicle design without finding numerous other applications of other weight-saving materials and techniques. However, these applications have occurred in a context of feature-driven weight gain as previously mentioned.

Thus, the fact that market forces and product strategies have yielded heavier vehicles each year since 1988 obscures the fact that mass-reduction technique is ubiquitous for vehicle systems and subsystems. Similarly, a single cost-range estimate for weight reduction opportunities obscures that fact that this area of technology is really an ever-evolving continuum of possibilities, from those at low or even negative cost on up to high-cost options used because their benefits delivers value for a given application. Steel has been the mainstay of the automobile for most of its 100+ year existence. However, steel is hardly a static technology, and improvements in applications of high-strength alloys as well as forming and joining processes offer numerous low-cost ways to reduce mass. Continuous improvement of material options and technique is also commonplace for other materials, including aluminum and plastics.
OVERVIEW OF IMPROVED STEEL TECHNOLOGY

The past several years have seen steady increases in the use of high-strength steels (HSS), many versions of which are referred to as high-strength, low-alloy (HSLA) steels. These materials plus their associated advanced design and fabrication techniques (as well as improved design and fabrication using traditional steels) formed the basis of the American Iron and Steel Institute (AISI) Ultralight Steel Auto Body (ULSAB) series of studies and demonstration projects. The ULSAB car body demonstrated a 19% mass reduction in a body structure that had superior strength and structural performance (including crashworthiness) along with a reduced parts count and net manufacturing cost savings compared to a conventional steel body.14 Comparable mass reductions and other benefits were achieved for doors, hoods, decklids, and hatchbacks.15 A companion project, the Light Truck Structure Study, also showed up to 19% weight reduction at a 20% cost savings with improved steel structures for body-on-frame pickups and SUVs.16

Responding to PNGV17 work targeting very aggressive mass reduction (such as 40% overall) using alternative materials such as aluminum and composites, AISI continued further development and demonstration of advanced steel technologies, resulting in the ULSAB Advanced Vehicles Concepts (AVC) study.18 Because many of the examples discussed in this paper are taken from existing vehicle programs, one might consider that a significant portion of the original ULSAB techniques have been incorporated into any recent model year baseline. However, the AVC analysis indicates that steel technology still has a long way to go before exhausting the opportunities for cost-effective mass reduction. EPA featured the ULSAB-AVC work as an example of "Green Engineering" and published an AISI case study outlining its benefits for highly cost-effective fuel economy improvement.19

Indeed, advancing steel technology continues to out-compete alternative materials, particularly in high-volume applications, even though lightweight metals are also seeing greater use overall. HSS is substituting for milder grades of steel, and also for iron in applications such as crankshafts. It has also begun to regain some market share previously lost to aluminum, in wheel applications, for example. In all cases, it provides cost-effective reductions in mass for a given level of materials performance (including strength, stiffness, durability, and resistance to wear). As noted earlier, however, the desire to improve performance metrics other than fuel economy means that net weight reduction is rarely seen, certainly not at the vehicle level and
often not even at the component level as parts become larger, stronger, stiffer or otherwise more functional (including better crashworthiness).

Ward's annual *Automotive Yearbook* has for many years included a brief materials overview section that provides a look at recent materials applications of note. The 2004 edition lists a number of HSS applications:

- HSS comprised 60% of the 2004 Chevy Malibu, up from only limited applications in the previous version of the car.
- The use of tailored blanks (see below, page 11) saw continued growth, including use on new models such as the Chrysler 300 and Dodge Magnum.
- Hydroforming (see page 10) also experienced growth in applications. GM introduced hydroformed steel rails in the 1999 redesign of the Chevy Silverado, and Ford used even larger hydroformed rails and other components in the 2004 redesign of the F-150.
- GM's Northstar V8 engine for Cadillacs now uses a steel rather than iron crankshaft.
- The 2004 Nissan Quest minivan uses advanced HSS.

More recently, the newly redesigned 2005 Honda Odyssey makes extensive use of HSS in its "Advanced Compatibility Engineering" (ACE) structure. The automotive trade press and engineering literature also regularly describe numerous examples of advanced steel applications, including several grades of HSS, uses of stainless steels, and advances in forming and assembly technique that allow improvements in part performance at lower mass and often lower cost as well. As noted above, the American Iron and Steel Institute and the Auto-Steel Partnership provide clearinghouses for coordinating research on new steel techniques and disseminating information on the topic. Their websites are among the sources cited here.

**Cost considerations**

Cost information is rarely reported publicly on current and planned applications; by nature, such information is proprietary to the OEMs and the involved suppliers. NHTSA may be able to obtain cost data on a confidential basis, but other interested parties such as ourselves are not in a position to obtain such information. However, some of the studies referenced here provide cost estimates that give a general sense of the cost-effectiveness of advances in steel technology.

In any case, current applications of these materials technologies and design strategies are *prima facie* cost-effective, as revealed by their implementation in current vehicle programs. Fuel economy is typically only one of several reasons, and may often not be the primary reason, for their implementation. Thus, questions arise regarding how costs should be allocated to fuel
economy vs. other objectives and how such allocations might change if fuel economy were elevated in importance as a design objective. Such questions are also beyond the scope of this paper. Again, however, their ongoing implementation indicates that these state-of-the-art steel technologies certainly fall within a reasonable range of cost effectiveness. Moreover, new steel technologies are implemented in a competitive environment that puts a premium on higher productivity. For that reason, it is not surprising that each new step of technology development offers benefits along multiple fronts, including reduction of both mass and cost.

The steel industry itself points out how the ULSAB work disproves what they term to be some big misconceptions. One is that weight gain is needed to make a stronger and stiffer body structure; the ULSAB projects development work cut 25% of the weight from a body-in-white while improving performance in twisting, bending and vibration tests compared with current technology. The project also refuted the notion that a lighter steel structure must be more expensive, projecting that a lightweight steel body-in-white would cost 15% less than one built only with conventional steels and processes.

**Material-based mass reduction often compounds benefits**

A weight savings in one part often creates a series of additional weight savings in other parts. This effect, termed "mass decompounding" is very important to understanding the full benefits and costs of weight-saving technology. For some innovations that are themselves more costly, the secondary savings can offset the higher cost, resulting in a less costly design overall. This mass decompounding effect is one reason why aluminum castings have seen steady growth in automotive applications, such as engine blocks, transmission cases, and suspension components. A lighter powertrain, for instance, requires less structural support, yielding additional mass savings throughout the vehicle in the body, suspension, and brakes. Similarly, the lighter body structures achievable with HHS and advanced fabrication techniques allows use of a lighter powertrain and suspension.

Many examples of compound benefits from lightweight steel technologies can be found in engines. The concepts are illustrated in the new inline 2.7L 4-cylinder engine Toyota is using in the 2005 Tacoma pickup. This vehicle, incidentally, won the Motor Trend 2005 Truck of the Year award and features a number of other innovations, including a composite bed liner.
The new Toyota 2.7L engine's valvetrain uses advances that reduce reciprocating mass, the direct weight-savings benefits of which are small, but which enable higher performance and efficiency. High-strength steel enables thinner valve stems, allowing the use of softer springs, which in turn enables hollow overhead camshafts, thereby enabling a lighter, smaller cam chain, also using high-strength steel. The resulting system is more compact and quieter than previous designs. The new Tacoma is larger than the previous model as well as more powerful in both of its engine configurations, and so the benefits of the technology improvements are not fully reflected in higher fuel economy. Nevertheless, reflecting the net effect of all of the vehicle's design changes, the 2005 model's CAFE ratings did rise to 26.9 MPG, up 15% from the 23.4 MPG rating of the 2004 model with 2.7L engine; the new engine delivers 164 HP compared to the previous engine's 150 HP.

The mass decompounding effect can apply to any component, and many more examples can be found in the automotive literature. The benefits are especially valuable for mass-saving technologies in engines, including design improvements for higher specific power. Significant mass-saving opportunities exist for engines that are traditionally larger and heavier, including diesel engines, as used in full-size pickups and their derivatives.

**RECENT ADVANCES IN LIGHTWEIGHT IRON AND STEEL TECHNOLOGY**

Improved steel materials and forming processes allow a significant optimization of vehicle body structures and components.

High-strength steel (HSS) is based on alloys that are categorized on the basis of yield strength. Standard HSS has a yield strength between 210 MPa and 550 MPa; ultra-high-strength steel (UHSS) has a yield strength higher than 550 MPa. High-strength steels can cost as much as 50% more than traditional mild steels, but they allow use of lower thicknesses than milder steels for achieving needed part performance specifications. Also, different grades of steel can be combined in tailored blanks (see below), so that the more costly or thicker materials can be placed only where needed. With HSS, there can be a trade-off between strength and formability; in other words, the stronger a steel is, e.g., in resisting stretching (tension), the more difficult it can be to forge into shapes, particularly the stylistically and aerodynamically optimized shapes needed for new vehicles. Steel suppliers are therefore developing steels with a range of properties that give engineers more flexibility in selecting an ideal grade of steel for any given application.
Advances in fabrication and assembly technique are just as important as advances in materials. For lightweight steel technology, key process advances include laser welding, hydroforming, and tailored blanks. Both tailored blanks and hydroforming allow parts counts to be reduced, providing significant savings on tools and dies, simplifying later stages of assembly, and improving the integrity of components, subassemblies, and body structures. These processes can be combined in the production of any one component or subassembly. All of these techniques were used in the aforementioned ULSAB series of projects demonstrating across-the-board improvements in steel technology for cars and light trucks.

Compared to conventional welding processes, laser welding creates a very clean and strong weld seam with minimum excess material. It is an important enabling technology used for multiple stages of steel materials fabrication and assembly. Laser welding permits production of new process input materials, such as tailored blanks, with smooth, high-integrity seams and minimal distortion or change in material properties surrounding the weld zone. It also improves strength, aesthetics, and overall quality of final assembled structures. As automakers gain experience with laser welding and the structural design improvements it permits, they are reaping significant productivity savings as well. A recently reported example is VW's use of the technology on the 2004 redesign of the Golf. Compared to the previous model, they reduced production time per car body by 25% while reducing weight.

A related innovation is greater use of steel tubes in place of shapes based on stampings of sheet steel. High-quality tubes are formed by bending sheets into a tubular shape with a laser welded seam. In addition to direct uses (e.g., in cross members and door beams), steel tubes also find broader use when further manipulated by hydroforming.

Hydroforming involves shaping a part in a die through the use of fluid pressure as opposed to stamping. Tube hydroforming permits the construction of relatively complex shapes with a single part that is stronger and lighter than the same part made as an assemblage of stampings. As one of the new fabrication techniques identified by the ULSAB project, hydroforming was scrutinized by automakers concerned about its costs and workability. An analysis by Rover group validated its applicability using the Freelander compact SUV as a case study. Although a number of challenges were identified, methods for overcoming them were found, with optimizations achieved using advanced CAD tools. Eight bodies were built for validation and testing purposes; the results demonstrated a small mass reduction with a 25%
increase in torsional stiffness. Such results suggest that a lighter structure could have been built without as great an increase in stiffness. An economic analysis showed that the demonstrated hydroformed design could be implemented within pre-defined financial targets, in other words, would be cost-effective for the given application. Hydroforming is now coming into widespread use and is particularly valuable for optimizing the frames of light trucks. GM and Ford have both used hydroforming for frame components in their full-size pickups and vehicles sharing those platforms; again, however, the potential mass savings were sacrificed to provide further increases in stiffness and other structural performance attributes.

**Tailored blanks** combine different grades and thicknesses of steel into a single blank, referring to a piece of material that is inserted into a stamping press or other piece of forming equipment. They allow optimizations of strength, crash performance, and dent resistance with minimal material use and therefore lower weight than attempting to make a similarly performing part from a blank of uniform grade and thickness. Tailored blanks also permit reduced major parts counts and simplified assembly. Instead of two or more different gauges being welded together to achieve the desired component, an integral component can be stamped or hydroformed from a tailored blank. This technique pushes some of the complexity upstream in the assembly process, but can do so with net cost savings and often substantial improvements in component performance (in terms of mass, stiffness, strength, etc.).

Sandwich materials, involving a plastic core between thin sheets of a steel skin, are another innovation that can be used to save weight. Although sandwich steel cannot be welded, it can be formed and joined through many other common processes and is used in applications where bending stiffness is the principle performance need. One branded version of this material is "Quiet Steel®," which uses viscoelastic cores in a laminated steel composite to offer significant cost reduction opportunities and enhanced NVH performance. A notable recent application is in the 2004 upgrade of Chrysler's Town & Country and Dodge Grand Caravan minivans. Driven by competition, Chrysler needed to add a stowable third-row seat and other refinements; steel sandwich material was used to make the tubs into which the foldable seats were stowed.

An overarching area of progress that enables further refinement in all aspects of iron and steel use is the major improvements in materials science, component characterization and modeling, and computerized simulation and design methods. Better techniques for measuring and modeling the properties of steels enable highly optimized designs. Such advances give
engineers greater confidence in part performance, minimizing the "margin of error" that otherwise results in a larger or heavier part than needed. Extensive computer modeling development and validation work yields CAD/CAE/CAM\textsuperscript{34} techniques that enable many fewer adverse trade-offs in design, resulting in simultaneous progress in weight reduction, strength, stiffness, and energy absorption as needed, while cutting materials costs and waste and enhancing productivity in both design and manufacture.\textsuperscript{35} Such design and engineering advances underpin the potential identified in the ULSAB and related advanced steel technology demonstration programs of AISI and the Auto-Steel Partnership. The potential for capturing such progress for net mass reduction is one of the key reasons why lightweight steel technologies can be very cost effective.

**Illustrative applications**

Highlighting a set of recent applications of lightweight steel illustrates the range of opportunity afforded by this area of technology. The fact that they have been put into production speaks to their basic cost-effectiveness and the fact that they are likely to be economically practicable in other applications. Although potential new and expanding uses of similar technology would have to be evaluated within the context of a given vehicle program, pointing out actual applications can guide a more formal assessment that might be carried out to better estimate the contribution of lightweight steel technology to future model year fuel economy.

The Honda Civic is one example of a high-volume vehicle using advanced steel technologies. It makes extensive use of high-strength steel, strategically placed cross members for distributing crash loads, and optimized crush zones.\textsuperscript{36} Honda targeted and achieved a 5-star frontal crash rating while producing a light weight structure as needed to maintain the Civic's high fuel economy. High-strength steel is used for approximately 50% of the body structure, including mid-floor cross members and floor gussets. Multi-directional cross members are tied together to create what Honda terms a "smart-linked" body shell. The vehicle's front subframe, which supports and surrounds the engine, was built with hydroformed members to make it both lighter and more rigid than a similar subframe fabricated with conventional stampings. The resulting design divides frontal collision energy between the parallel side frame and subframe, efficiently absorbing the impact while maintaining a rigid passenger cage. High-strength steel cross members were also used for enhanced side impact protection.
One light truck example is the Jeep Grand Cherokee, as noted above in the Introduction. Chrysler Division highlighted the lightweight steel techniques used for the 1999 redesign, which ran through model year 2004.37 The company described its use of a unibody for this SUV, in contrast to the body-on-frame approach used by its prime competitors, noting how the unibody offers better ride and handling and is quieter and more refined.38 The company made increased use of tailored blanks and other lightweight steel techniques. These advances enabled it to have improved structural strength, reduced weight, less noise, vibration and harshness, better energy-absorbing front and rear impact zones with a rigid passenger safety cell—all with a net reduction of weight. The resulting body-in-white was 50 pounds lighter than the previous-generation model; torsional stiffness increased 20% (important for ride and handling); upper door frame and liftgate frame stiffness were increased by even greater amounts (also important for handling as well as for fit, quietness, and refinement). High strength steel side-impact beams were used in all four doors. Chrysler Division noted its use of computer simulation techniques to help achieve these improvements. Although engineering cost information was not provided, the vehicle is a high-volume, mid-market product and so use of these advances at the time reflects on their cost-effectiveness. The Grand Cherokee example is given here not because it was necessarily exceptional, but because it was a steel technology application that was highlighted by the company. The techniques are being used throughout the industry and undergo continuous improvement.

Another example of cost-effective lightweight steel techniques is given by a design study for a liftgate, one of many parts for which a combination of stiffness and lightness is an important objective.39 It is an instance of how tailored blanks, made by laser welding together different grades or thicknesses of steel, play a role in such component optimization. They offer cost-effective ways to reduce mass and material use (including elimination of reinforcements often needed in conventional single-grade stamping based designs) while improving structural performance. Using tailored blanks also yields productivity benefits such as reduced inventory, savings in die development, and less floor space. Assembly costs were reduced as were overall manufacturing costs for what is a better performing— including lighter—part. The study is one from which a cost-effectiveness datum can be derived: it concluded that a 1.64 lb mass reduction was achievable with a $1.72 cost savings, implying a savings of $1.05/lb, i.e., a negative cost for weight reduction.
GM has for several years been increasing its use of HSS and improved fabrication techniques in light trucks. Use of ultra-high-strength steel in front-door impact beams on its extended-cab pickups gave a 22% weight savings and reduced the number of parts needed. GM pioneered its use hydroformed frame rails in the 1997 redesign of the Chevy Corvette. But the benefits of and confidence in the technology were such that they used it for the front frame rails and cross-members in the 1999 redesign of the Chevy Silverado, North America's highest volume (over 1-million units annual) production platform. Improvements were made in other parts of these full-size truck frames, for which GM "mixes and matches" four front sections, two middle sections, and two rear sections to create over a dozen different pickup and SUV variants of the Silverado family. An improved roll-forming technology was used to make the HSS middle rail sections. Tubular cross-members help reduce weight in the rear section, which otherwise used conventional stampings.

The potential for an even greater step forward in making lighter truck frames was identified in the Auto-Steel Partnership sponsored Lightweight SUV Frame study. The starting point was a Ford Expedition frame and the project sought cost-effective ways to reduce mass and improve other performance characteristics in a new frame design that could be adapted to such a vehicle with minimum impact on packaging and other aspects of the balance of the vehicle. The study noted that in spite of various improvements, the basic design of the large light truck frame has not changed much in the past 25 years. Newly developed advanced computerized engineering tools were used to develop a new design, which incorporated significant amounts of HSS. The resulting design showed a 23% reduction in frame mass achievable at an estimated cost of $0.31/pound.

**Lightweight steel use in engines**

Numerous engine components have for years been made of iron and steel, but refinements in materials and technique are enabling significant improvements, including lighter weight for a given level of performance. Advanced steel technologies are being used in flywheels, crankshafts, camshafts, cam followers, connecting rods, rockers, valves and valve springs, variable timing systems, drive chains, and fasteners.

AISI documented such uses of improved steel technologies in a report released last year, including examples drawn from applications in the award-winning engines highlighted by *Ward's" 10 Best Engines" for 2004*. Again, the fact that this technology is being widely used in
mainstream vehicle programs speaks to its cost-effectiveness even though specific cost information is not publicly available. Connecting rods provide one example in which using a specialty steel reduced mass by 10% while enhancing durability and performance. These findings are from an AISI-sponsored study that applied finite element analysis and other computational techniques to select the type of steel and optimize part design. They estimated a 25% cost savings for this improved part compared to a conventional connecting rod.

**Compacted Graphite Iron**

Compacted Graphite Iron (CGI) is an iron-based material that incorporates graphite and sometimes other materials (e.g., small quantities of titanium). Its distinctive microstructure makes it as much as 80% stronger, 40% stiffer, and twice as fatigue-resistant as ordinary cast iron. Although the material has been in limited use for decades, advances in metal casting and machining techniques are now enabling it to break into use in high-volume production. A sample of recent engine block applications indicates a range of 10%–29% (median 15%) weight reduction compared to conventional cast iron. Other potential applications include piston rings, exhaust manifolds, brake components, flywheels, housings, and brackets. CGI is particularly useful for diesel engines where its strength and resistance to distortion is well suited to the higher pressures. It permits a 10% increase in peak firing pressure compared to conventional iron. The durability advantage is even more pronounced compared to other new engine block and cylinder materials, such as those based on aluminum silicates, which have been used because of their lighter weight.

As of 2002, only about 5,000 vehicles in Europe (some Audi and BMW models) had CGI applications. Traditional barriers to higher-volume, lower-cost production techniques have included the difficulty of casting and machining the material. However, advances in foundry and machining processes are overcoming these barriers. As diesel vehicles in Europe face a continuing need to deliver higher efficiency at minimal weight, CGI enables engine blocks to be built with thinner walls while exploiting the material's ability to withstand higher cylinder pressures without distortion. Increasing use of diesels is one important strategy for improving light truck fuel economy in the United States. As diesel engines are redesigned or newly designed for an emerging light duty market, use of CGI presents an opportunity to deliver even higher efficiency in these applications. It could also improve the fuel economy of existing light
truck diesel engine applications, including those in Class 2B pickups which already have a high diesel share.

**Steel holding its own against aluminum for wheels**

Through 2001, aluminum had been steadily gaining share from steel as the material selected for wheels, exceeding 50% of new vehicle wheels by 1999. The past few years, however, have seen a reversion back to steel as improved designs using HSS and new techniques have enabled the material to meet the weight and performance targets needed for new vehicles.50

The applicable technologies include several new forms of high-strength and advanced high-strength steels, as well as new wheel designs offering large ventilation openings and mimicking the thin-spoke appearance of some performance-oriented aluminum alloy wheels. Advances in technique that make lighter weight steel wheels possible include improvements in simulation software, allowing more precise designs, as well as improved CAD/CAM systems, enabling the designs to be executed with a high degree of uniformity and dimensional precision. All OEM's are using and revisiting steel wheels; key suppliers include Hayes Lemmerz and ArvinMeritor, and AISI has been involved in coordinating with automakers and suppliers to spur further development of competitive steels and techniques to better fend off competition from other materials.

Both fuel economy and performance are key technical factors motivating weight reduction in wheels, the design of which must also consider strength, wear and corrosion resistance, handling and suspension performance considerations. But very important factor in wheel design is styling: the wheel is a prominent visual feature of a vehicle and so crucial for overall impression and marketing. According to AISI, the new steel designs can meet all quality and performance targets as well as come close to and sometimes below mass targets while saving as much as $100 per wheel compared to aluminum. In other words, levels of mass reduction comparable to those previously achieved with aluminum are now available at lower cost.
CONCLUSION

Recent and ongoing advances in steel and iron-based technologies enable significant, low-cost mass reduction in a broad range of car and light truck applications. These technologies are a routine part of automotive engineering practice and allow vehicle lightweighting while simultaneously improving other aspects of structural performance, including crashworthiness and crash compatibility, utility, ride, handling, and reduced noise, vibration and harshness. The extensive application of these technologies in high-volume vehicles speaks to their cost-effectiveness. Although this paper is not able to provide specific cost information, it is clear that these evolutionary refinements offer automakers ways to cut weight at low cost and often cost savings.

For competitive reasons, the steel industry and steel component suppliers are heavily investing in innovation. They offer successful design solutions incorporating high-strength steels, stainless steel, new formulations of iron, and an associated variety of new design, fabrication, and assembly techniques. As for other aspects of vehicle technology, whether or not a net fuel economy gain (from net weight reduction) results from use of state-of-the-art steel technologies depends on the extent to which fuel economy is a design objective. For future model years, a gain in fuel economy could be realized by redirecting some of this ongoing progress in lightweight steel technology toward net weight reduction. Because these advances in steel technology enable weight reduction while maintaining size and improving strength and other crash mitigation aspects of structural performance, these fuel economy benefits can be achieved while continuing to make progress on safety.

Weight savings obtained by broader application of demonstrated best practices would be very cost-effective. This conclusion contrasts with that of the NRC CAFE panel, which did not appear to consider what is actually going on in the auto industry with respect to materials-related areas of engineering. The review given in this paper suggests that weight reduction opportunities can be viewed as a continuum, ranging from very low cost (even zero or negative cost) options to higher cost options. More fully characterizing and quantifying the potential fuel economy gains from ongoing progress in steel technologies is a worthy topic for further analysis.
ENDNOTES


2  NHTSA uses similar estimates of the sensitivity of fuel economy to mass reduction, giving fuel economy increases of 6% (performance-adjusted) and 3% (unadjusted) per 10% weight reduction; see Final Economic Assessment, Corporate Average Fuel Economy Standards for MY 2005-2007 Light Trucks, Section V (http://www.nhtsa.dot.gov/cars/rules/rulings/CAFE05-07/FEA/Chapter05.html).


4  NHTSA op. cit. (Final Economic Assessment, Section V).

5  EPA. Light-Duty Automotive Technology and Fuel Economy Trends, 1975 through 2004, April 2004, Table 2. These statistics reflect only the currently CAFE-regulated light trucks, up to 8500 lbs GVW, and do not reflect possible growth in or up-sizing of vehicles in the Class 2B segment.

6  Murrell, J.D., How fuel economy responds to changes in weight, CID, and N/v, U.S. Environmental Protection Agency, Ann Arbor, MI, 1990; the 4% sensitivity estimate accounts for drivability considerations (low-end torque constraints); a larger sensitivity factor of about 6% would be derived on the basis of only peak power-to-weight ratio.

7  EPA op. cit., p. v.


9  op. cit., quoting Sue Cischke, Chrysler Division Executive Director for Vehicle Certification, Compliance and Safety Affairs (Cischke is presently Ford Motor Company Vice President for Environmental and Safety Engineering).


11  NRC (2002), Tables 3-1 to 3-3.


17  PNGV is the Partnership for a New Generation of Vehicles, a government-industry partnership initiated by the Clinton Administration in 1993.


21  See www.autosteel.org is the American Iron and Steel Institute's automotive applications site and www.a-sp.org is the site maintained by the Auto-Steel Partnership.

22  In addition to gains from materials processing improvements, productivity in auto body and part manufacturing is growing as the number, sophistication, and capabilities of intelligent automated tools continues to rise; see, e.g., "Robot numbers rise as costs tumble," Automotive News, 21 February 2005, p. 26.

ENDNOTES, CONTINUED


25 Ultralight Steel Auto Body, Final Report (op. cit.)


27 These process advances—laser welding, tailored blanks, and hydroforming—can also be applied to aluminum, and similarly represent ways to enable aluminum based components and structures to become more cost-effective.


31 See Materials Sciences Corp., "Quiet Steel®" (www.quietsteel.com).


34 CAD = Computer Aided Design; CAE = Computer Aided Engineering; CAM = Computer Aided Manufacturing.


37 Further progress in materials and structures was undoubtedly made for the 2005 Grand Cherokee redesign, but the company did not appear to release as much information on these topics as it did for the 1999 redesign.


47 ECS. "CGI's growth could change iron's face," _Engineered Casting Solutions_, Fall 2004 (www.castsolutions.com).

48 op. cit., Table 1.

49 Mortimer, op. cit.