Vehicle Design Strategies to Meet and Exceed PNGV Goals

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ABSTRACT

A host of important and interactive factors contribute to the successful design of any production vehicle. However, the combination of hybrid-electric drive and low-drag platform design, with emphasis on vehicle mass and drag coefficient reductions, appears prerequisite to the simultaneous optimization of efficiency, emissions, performance, and cost. This paper examines the fundamental relationships between these and other design elements, such as series *vs.* parallel hybrid configurations, energy-storage mass, and safety. The intent is to present an approach to vehicle design that can yield marketable, production-worthy, high-performance automobiles while meeting or exceeding goals set by the Partnership for a New Generation of Vehicles (PNGV). Rather than attempting to push the envelope of maximum efficiency, this paper explores technologies and design strategies for baseline and further optimized design scenarios within the PNGV time frame and design criteria.

INTRODUCTION

The emergence of new materials, processes, and technologies and their projected price reductions, in conjunction with previously unavailable high-efficiency electric drivesystems, power electronics, and engines, presents an unparalleled opportunity for a largely new approach to automotive design.

The PNGV is a cooperative government/industry effort to develop automobiles with three times the current average fuel economy, without sacrificing desirable attributes. This is actually Goal 3 of the jointly funded partnership. Goal 1 focuses on advanced manufacturing technologies, while Goal 2 focuses on near-term improvements in automotive efficiency, safety, and emissions. Goal 3 will draw upon the work done in pursuit of Goals 1 and 2, which may in turn apply the R&D work for Goal 3 to near-term conventional vehicles, whenever commercially feasible, to improve the competitiveness of U.S. automotive technology and manufacturing.

Analysis at Rocky Mountain Institute (RMI) suggests that the PNGV may be placing too little emphasis on, or underestimating the importance of, both a systems optimization approach and some key design variables. Low-drag platform design and the documented mass reductions and structural parts consolidation offered by new materials, coupled with mechanically simplified, smaller, cleaner and higher efficiency hybrid-electric propulsion, may be the solution. This approach, though challenging, appears to make the cost-competitive mass production of marketable automobiles meeting or exceeding PNGV goals both feasible and desirable.

Current PNGV goals include a body-in-white (BIW) mass reduction of 50%. This is reasonable given relatively conservative assumptions and the established design criteria. The PNGV goal of 40% reduction in *curb mass*, however, appears to be not only low but also a suboptimal design strategy. If careful attention in design is paid to component optimization and mass decompounding, curb-mass reductions of 50–55% (based on a BIW mass reduction of ~55%) appear feasible within the PNGV time frame. While the additional 10–15 percentage points of curb-mass reduction may not directly improve fuel economy more than about 5–10%, it could be an important enabling factor for the cost-effective application of key propulsion technologies. To the extent that this is true and crashworthiness can be sufficiently addressed, plausible curb-mass reductions of 60–65% may be more appropriate.

The current goals also appear to be under-emphasizing potential improvements in aerodynamic drag, rolling resistance, and other important variables. Although the strategies used by PNGV participants to achieve up to three times the current average family-sedan fuel economy will very likely change with new research, the initial “3-times Design Space” chart included in the *PNGV Program Plan* and subsequent presentations at least implies this distribution of emphasis and parameter optimization. The program plan does, however, acknowledge the potential importance of design parameters not yet included and the first-pass nature of the specified “practical limits.” This paper is in part an effort to describe some of what might advantageously be included or further emphasized.

Because recent prototype vehicles, such as the 1991 GM Ultralite concept car, demonstrate advanced materials applications and significant mass savings, along with excellent packaging efficiency and low aerodynamic and rolling drag, they will provide benchmarks in the discussion of practical limits for some design parameters. Departures of PNGV design criteria and production vehicle requirements from these benchmarks will be considered.

Criteria are established for performance and safety. Platform design considerations, selected component and design parameter sensitivities, and market limitations for meeting established criteria are discussed. Hybrid-electric drivesystems are presented as a means of maximizing benefits from synergies between platform and drivesystem parameters.

Conclusions regarding vehicle design that are not referenced to the literature are based on the findings of this and prior analyses at RMI, and on the primary author’s experience in design and fabrication of hybrid-electric vehicles at Western Washington University's Vehicle Research Institute.

Illustrative vehicle scenarios are modeled using Rohde and Schilke's hybrid vehicle model (from General Motors Systems Engineering) and SIMPLEV (from Idaho National Engineering Laboratory) to provide fuel efficiency data which approximate real-world driving conditions. A limited number of well-documented representative technologies and a detailed hypothetical mass budget provide the data to calculate the results for a range of design scenarios. Selected sensitivities for fuel economy are based primarily on the Rohde and Schilke model and then checked and re-normalized against the more comprehensive and accurate SIMPLEV model. Performance calculations are based on relatively simple spreadsheet models developed at Rocky Mountain Institute.

NOMENCLATURE

PNGV	Partnership for a New Generation of Vehicles
CARB	California Air Resources Board
EPA	US Environmental Protection Agency
ULEV	Ultra-Low-Emission Vehicle
ZEV	Zero-Emission Vehicle
VZEV	Virtual Zero-Emission Vehicle
FUDS	Federal Urban Driving Schedule
CTL	Concord, Taurus, Lumina benchmark 1995 MY sedans
BIW	Body-in-white, *including* closures
C_D	Coefficient of aerodynamic drag (dimensionless)
A	Frontal area (m^2)
M	Vehicle curb mass (kg)
M_{EPA}	EPA test mass = curb mass + 136 kg for 2 occupants
r_0	Coefficient of rolling resistance (dimensionless)
BEV	Battery-Electric Vehicle (recharged from utility grid)
HEV	Hybrid-Electric Vehicle (converts fuel to electricity)
APU	Auxiliary Power Unit in a hybrid drivesystem
BSFC	Brake Specific Fuel Consumption
LLD	Load Leveling Device for energy storage in an HEV
SOC	State Of Charge for energy storage devices
DOD	Depth Of Discharge for energy storage devices
IM	Asynchronous Induction Motor
PM	Permanent-Magnet motor
SR	Switched Reluctance motor
IC	Internal Combustion engine
HVAC	Heating, Ventilation, and Air-Conditioning system
ABS	Antilock Brake System
BTU	British Thermal Unit
BHP	Brake Horsepower (auxiliary loads included)
mpg	Miles per U.S. gallon of gasoline or energy equivalent
ton	Metric ton or 1000 kg
psi	Pounds per square inch

PERFORMANCE AND SAFETY CRITERIA

PNGV Design Criteria

The PNGV has established design criteria as a common element of Goal 3 for all of the major U.S. automakers, suppliers, small manufacturers, independent research organizations, and government laboratories involved. The design criteria describe the agreed level of performance, utility, and cost that must be maintained in the production prototypes which each of the Big Three automakers will attempt to build by the year 2004. It is important to note that *production prototypes* are specified, which indicates that methods, materials, and components used must be appropriate for, or at least the precursors of, high-volume production. A concept vehicle from each maker, not necessarily meeting all of the stringent requirements of the production prototype, is to be completed by the end of the year 2000.

The most fundamental criterion is that the vehicle must achieve three times the 26.6 mpg average fuel economy of comparable current family sedans, or about 80 mpg. The 1995 model-year (MY) Chrysler Concord, Ford Taurus, and Chevrolet Lumina are used as benchmark current family sedans and will be referred to from this point forward as the CTL. If alternative fuels are used, the fuel economy goal can be expressed as 80 miles per 114,132 BTU.

The vehicle must meet the following performance criteria (PNGV Program Plan, 1994):

- Emissions at or below Tier II default levels of 0.125 g/mi HC, 1.7 g/mi CO, and 0.2 g/mi NO_x.
- Compliance with all present and future (up to date of production) FMVSS safety standards.
- In-use safety performance (handling, tire adhesion, braking, etc.) equivalent to the CTL.
- Family sedan function, defined as the ability to carry up to six passengers with a level of comfort and cargo capacity (475 l; 16.8 ft^3) equivalent to the CTL.
- Load-carrying capacity, including six passengers (passenger weight is undefined by the PNGV: we assume 68 kg each, as in EPA test mass used for modeling and elsewhere in this paper) and 91 kg of luggage.
- Gradability (not yet specifically defined) and drivability at sea level and at altitude equivalent to the CTL.
- Acceleration of 0–60 mph (~0–100 km/h) in 12 seconds or less at EPA test mass (curb mass, including a full fuel tank, plus 136 kg for two occupants).
- Combined urban/highway range of 380 miles (610 km) on the 1994 Federal Driving Cycle.
- Ride, handling, and noise, vibration, and harshness control equivalent to the CTL.
- Recyclability of 80% by weight (five percentage points above today's industry average).
- Minimum useful life of 100,000 miles (160,000 km), and service intervals and refueling time comparable to or better than the CTL.

It also must have customer features, such as climate control and entertainment systems, and total real cost of ownership, equivalent to the CTL.

Design Criteria for This Analysis

For the most part, the stated design criteria for the PNGV focus on, but are not limited to, *uncompromised* performance rather than *improved* performance. RMI's analysis suggests that the advanced vehicle design options under consideration by the PNGV could substantially improve performance not only in fuel economy and emissions but also in acceleration, handling, braking, safety, and durability. And there is one overall criterion of marketability not spelled out by the PNGV, namely that the vehicles must not only be *equivalent* to the CTL, but be in some way *more* attractive to customers. Since fuel economy and emissions are low on the list of purchasing criteria for most consumers today, and may become even lower in the future, the vehicles must be better in other respects if they are to gain the large market share required to provide significant societal benefits, such as cleaner air or reduced dependence on imported petroleum. This paper thus uses the PNGV criteria as a baseline and adds the following:

- Acceleration from 0–60 mph in less than 9 seconds at EPA test weight, and less than 13 seconds at gross weight including six 68-kg occupants and 91 kg of luggage. This would be possible with the combination of low curb mass and road loads, and the performance characteristics of advanced hybrid drivesystems. It is also reasonable to assume that acceleration performance such as this will be relatively common by the year 2005, given that the current *economy class* Pontiac Sunfire SE and Chevrolet Cavalier accelerate to 60 mph in 9.4 and 9.5 seconds, respectively.
- Gradability sufficient to maintain 65 mph on a 6% grade at EPA test weight, and diminishing to no less than 50 mph at gross weight as defined above. Acceleration time should also be reasonable on grades to facilitate safe merging on inclined highway entrance ramps, suggesting 0–60 mph acceleration in 20 seconds or less at gross weight on a 6% grade. This is both what we estimate is appropriate and a guess at what the Big Three might agree upon for the yet-to-be-specifically-defined PNGV gradability criteria.[1]
- Improved handling, maneuverability, and braking, made possible by low curb mass and the 4-wheel ABS and traction control options available with hybrid drivesystems.
- Substantially improved crashworthiness relative to the CTL (at least in collisions with stationary objects), interior safety features, and ease, speed, and safety of post-crash extrication. Specifically, such vehicles should provide equivalent safety when colliding head-on with vehicles of average mass at the time of introduction. This may require absorption of several times the static crash energy in a dynamic collision with a vehicle weighing nearly twice as much (assuming a curb mass reduction of 40–50% from MY 2005 average, which will very likely be less than today's average). This appears to be possible with a combination of low vehicle mass, polymer-composite or light-metal occupant protection and energy-absorbing structures, and numerous other design considerations.

We will also consider a 'further optimized' vehicle design scenario closer to the edge-of-the-envelope hypercar (formerly supercar) concept that has been promoted by Rocky Mountain Institute (Lovins & Lovins, 1995; Lovins, 1995a; Lovins, 1995b). The further optimized vehicle scenario differs from the PNGV criteria primarily in its optimization of interior space for four to five adult passengers, rather than five to six. Other assumptions for this scenario, including further reduced vehicle mass and aerodynamic drag, will be discussed.

PROPULSION SYSTEMS TECHNOLOGIES

The unprecedented effort by major automakers, component suppliers, related industries, and government laboratories to meet recent legislative mandates for ZEVs and ULEVs has brought about major advances in electric and chemical-fuel propulsion systems. Examples include lightweight electric motors and controllers with *system* efficiencies over 90% for much of their usable range (Cole, 1993a); combustion engines capable of maintaining efficiencies of 40% or more, over a wide range of speeds and loads, while far surpassing ULEV standards (STM, 1995); and energy storage devices capable of meeting real-world vehicle requirements with careful systems design integration (Burke, 1995). Many of these technologies would be overly complex and very likely cost-prohibitive if simply applied to conventional or heavy battery-electric automobiles. Yet the combination of platform design improvements, lightweight materials, *and* hybrid drivesystem technologies provides an ideal and potentially cost-effective opportunity to take full advantage of these advances.

Conventional, Battery-Electric, or Hybrid-Electric Drive?

The PNGV design criteria for efficiency, emissions, performance, range, and cost markedly affect drivesystem selection. The PNGV goals do not include a requirement for "zero-emission" or electric-only range, and it is our contention that, as explained below, the necessity of sufficient electric storage capacity for even a modest range might preclude meeting all of the PNGV criteria. Nor, however, is combustion-free range necessary under newly proposed VZEV standards (CARB, 1995). Thus, we will not consider electric-only range except as a fringe benefit of some designs.

Conventional automotive drivesystems based on an internal combustion engine mechanically coupled to the drive wheels through a multi-speed transmission suffer from a combination of the inflexibility and complexity of mechanical systems, and inability to recover braking energy. To provide ample power for acceleration and gradability with a limited number of gear ratios, the IC engine must be oversized to roughly ten times what is required to cruise at 60 mph on a level road and three or four times what is required to maintain 60 mph on a 6% grade. It isn't possible to optimize the engine for all of the speed and load range combinations under which it must operate. Although substantially improved by electronic fuel injection systems, efficiency is diminished and emissions levels are elevated for many segments of the engine map.

The gross oversizing of the engine results both because the engine must cover the entire peak load and because peak power for an IC engine occurs at a fixed engine speed which would only be available at all wheel speeds if the transmission ratio were continuously variable. While making the peak power output of the engine available over a broader range of vehicle speeds and allowing the engine to be optimized to operate at a more or less a single speed, continuously variably transmissions typically have poor efficiency and do nothing to reduce the peak power required, so they are of limited value for improving fuel economy. Automatic transmissions with torque converters and multiple gears in series take the burden of matching engine output to vehicle speed off of the driver at a further efficiency penalty. The inherent drawbacks of conventional automobiles emerge even more sharply when contrasted with BEVs and HEVs.

The benefit common to both battery-electric and hybrid-electric drives, as compared to conventional systems, is their ability to recover a substantial portion of braking energy and store it for later use. But, aside from regenerative braking, BEVs and HEVs satisfy very different criteria.

Well designed BEVs can have per-mile emissions and efficiency advantages over current conventional vehicles, and

[1] There may also eventually be PNGV criteria for gradability with a trailer in tow. Based on the current rated towing capacity for the Ford Taurus, such a criterion might require the vehicle to tow a 450-kg trailer up a 6% grade while loaded to gross weight, and still maintain 45 or 50 mph. However, given the infrequency with which family car owners tow such loads, trailer design mass optimization and self-powered trailers may be a more appropriate focus for such design criteria than the towing vehicles.

may have similar advantages over HEVs, depending on the specific vehicle design and the mix of powerplants assumed to be recharging the BEVs. The former conclusion is generally agreed upon if the energy is measured when it's fed into the vehicle, rather than from the original source, although with widely varying results depending on the regional mix of powerplants assumed and how conventional technology is defined[2] (EPRI, 1994). The latter conclusion is a subject of considerable debate and is a complex topic warranting careful investigation not attempted in this paper.

The problems BEVs face in meeting PNGV goals center on performance, range, and cost. Vehicles such as the GM Impact BEV easily satisfy acceleration and gradability, but not load-carrying capacity, interior space, and range requirements. While the cost for mass-produced versions of such BEVs might eventually be acceptable, it isn't clear whether batteries with low enough replacement cost or long enough life under deep discharge conditions are feasible. The even more fundamental disadvantage of BEVs relative to HEVs is that the substantial mass of batteries required for even *unacceptable* vehicle ranges (under PNGV criteria, though perhaps not for a significant segment of drivers) drives up the size, weight, and cost of other components for a given level of performance. As designs move towards acceptable range and performance, the mass of the battery pack snowballs until almost every component and structure in the vehicle becomes bigger, heavier, and more expensive than is desirable. The consumer would pay for excessively high-power drivesystem components just to maintain good performance when carrying a sufficient battery pack for range. Furthermore, much of the energy storage capacity of the batteries is required simply because of the burden that the mass of the battery pack itself places on vehicle range. So BEVs, much like conventional cars, waste much of their performance and energy storage potential on transporting their own mass. Other energy storage devices, such as flywheels and ultracapacitors, have the high specific power needed for performance, but have only enough specific energy capacity to function as load-leveling devices (LLDs) which might extend the life of the battery pack. (Energy storage capacity in flywheels is similar to that of mid-range batteries, but higher cost per kWh precludes the installation of numerous flywheels.) Thus range and performance, as limited by mass, cost, and packaging constraints, preclude BEVs from meeting PNGV criteria.

The fundamental advantage, again, of hybrids over BEVs is the 50–100 times higher specific energy of stored liquid and even gaseous fuels over current battery technology. Thus HEV performance and efficiency are not impaired by a massive battery pack, nor is their range limited by the electrochemical energy storage technology. Infrastructure and fueling time limitations may also be eliminated, depending on the fuel used. Because HEVs' control strategies allow a load leveling device which needs high peak power but very little energy storage capacity, there is also the potential for a much lower cost per vehicle relative to that of a BEV.

HEVs, like BEVs, can suffer from a compounding of size, mass, and cost, plus added complexity, if care is not taken to optimize the design for low mass from the beginning (Lovins, 1995a). This has unfortunately been the case for many HEV prototypes. They are typically built from heavy BEVs or conventional platforms, adding numerous new components without taking advantage of the synergistic benefits of hybrid drivesystems. Ultralight design is thus the key to a successful BEV, but the BEV must be an HEV (storing energy in fuel rather than batteries) to be ultralight.

For this reason, HEVs with a series configuration (no mechanical connection of the APU to the wheels), and thus no need for significant 'battery-only' range, have an added advantage over BEVs relative to their parallel-configured counterparts. Series versus parallel hybrid configuration and their respective potentials for gain over conventional automobiles will be further discussed below in connection with hybrid drivesystem configurations and control strategies.

BODY-IN-WHITE STRUCTURE: MATERIALS AND MASS REDUCTION

Weight-saving and parts-consolidation technologies for high-strength and carbon steel, aluminum production and fabrication technologies, and polymer or metal-matrix composites technologies all contribute to the potential for reductions of vehicle curb mass by 2–3-fold (Lovins, 1995a). This section is not intended to be a thorough discussion of automotive applications for structural materials (Lovins *et al.*, 1995), but rather to introduce some of the reasoning behind the mass reductions which we consider feasible for the body-in-white (BIW). Although many do not meet the PNGV criteria for interior space and load-carrying capacity, the table which follows shows examples of what has been achieved with one-off prototype vehicles using alternative materials.

[2] For example, this might not hold true if comparing a heavy BEV with a lightweight car mechanically driven by a direct-injection diesel engine (DaimlerBenz, 1995; BMW, 1991).

Builder	Seats	Materials	BIW mass (kg) with closures...		Curb mass (kg)
			excluded	included	
PNGV target for 2004 pre-production prototype	5–6	Carbon, aramid, glass, aluminum, etc. (To be determined)	138	186 (Taurus –50%)	854 (Taurus –40%)
Ford Taurus, 1995 MY	5–6	Steel	271	372	1,423
Ford Taurus AIV, 1994	5–6	Aluminum	148	198	1,269[a]
IBIS Assocs. estimate, 1994	4–5	E-glass, etc.	236	—	1,218
GM Ultralite, 1991	4	Carbon, etc.	—	191	635
Esoro H301, 1994–95	4	75% glass, 20% aramid, 5% C	72	120–150 [b]	~500[c]
Renault Vesta II, 1987	4	Steel, Al, plastics, composites	—	—	476
WWU VRI Viking 23, 1994	2–(4[d])	Carbon, ~5% aramid	—	93	864 incl. 314 batts.
Kägi OMEKRON, 1989–90	2	Carbon, aramid	34	—	490 incl. 260 batts.
RMI PNGV Scenario; Further Optimized Scenario	5–6 4–5	Carbon, aramid, glass, aluminum, etc. (to be determined)	—	170–196[e] 123–143[e]	700 [f] nearterm 520 midterm

a) Assuming no component optimization or mass decompounding. **b)** Including two bumpers, four composite seat shells, and ~30 kg removable from the original bumpers and double-hinged doors as estimated by the builder. **c)** If redesigned from a 670-kg[b] range-extender parallel hybrid with 230 kg of batteries to a series hybrid with a 50-kg LLD, assuming improved performance and no mass decompounding (which would be available). **d)** A series hybrid not needing this design's large battery, 0.9-liter IC engine, and glass/aluminum CNG tank might instead use the same structural mass budget to carry 4+ passengers. **e)** Includes 26 kg safety structures, 8 kg hardpoint mounting inserts, and 3 kg elastomeric bumper skins. **f)** Includes a relatively heavy version of the STM Stirling engine (76 kg) and a 63-kg LLD.

Steel

The American Iron and Steel Institute (AISI) claims that with a "holistic" approach to design, *vehicle* curb-mass reductions up to 40% can be achieved (AISI, 1995). This says perhaps less about AISI's confidence in steel BIW mass reduction than about its confidence in compounding mass reduction for *non*-structural vehicle components and systems. Porsche Engineering Services, as commissioned by AISI, has calculated the "realistic achievable potential" for BIW mass reduction to be 15–20%, with a theoretical maximum of ~30% (AISI, 1994). Unfortunately, this is still not sufficient to meet the 50–55% mass reduction goals proposed for the BIW by the major participants of the PNGV (Gjostein, 1995b). While not meeting the interior volume criteria for the PNGV, vehicles such as the 1994 Honda Civic with BIW mass not much over 200 kg have demonstrated the potential for much lighter-than-average steel cars. There is no evidence yet, however, that mass reductions similar to those attainable with aluminum or polymer composites can be achieved with steel, given the PNGV design criteria.

There is already a vast body of knowledge surrounding the use of steel in the automotive industry. With about 14% of its sales to automakers, the steel industry has too much at stake not to continue improving its product in response to competition from aluminum and composites. Steel also has the advantage of strain-rate sensitivity, which helps steel cars safely absorb a range of impact forces. Competition from aluminum and composites, then, ought to produce some impressive improvements for near-term steel car production, particularly regarding design attention to part thickness, parts consolidation, joining processes, and occupant safety. These improvements will also be fed by the automotive industry's need to amortize investments in steel BIW manufacturing.

Aluminum

Ford's 199-kg Taurus/Sable AIV (Aluminum Intensive Vehicle) BIW with closures has already demonstrated a 47% mass reduction for a mid-sized vehicle (Gjostein, 1995a). This was accomplished without even taking full advantage of mass decompounding that would result from downsizing the engine and chassis components (since they no longer need to accelerate, carry, or stop as much mass) and thus allow further BIW mass reduction. The aluminum BIW for Volvo's five-passenger hybrid ECC (Environmental Concept Car) also weighs about 200 kg, has sufficient strength to carry a 350-kg battery pack, and is also engineered for excellent crashworthiness (Volvo, 1992). Further analysis suggests that BIW mass reductions up to 55% using aluminum may be technically feasible for high-volume production automobiles by the year 2000, although the economics of doing so are still uncertain (Sherman, 1995).

Aluminum has a tooling-cost advantage over steel because it can be easily extruded, with inexpensive cast nodes to connect extrusions, or hydro-formed into relatively complex shapes. Thus fewer expensive stamping dies would be required. While spaceframe designs minimize tooling costs by taking advantage of inexpensive extrusions, they are inherently a less efficient use of materials than unibody or full monocoque designs. Once a spaceframe has been paneled with sheet material of an appropriate stiffness for mounting components and compartmentalizing passengers, drivetrain, and wheels, along with exterior panels for aerodynamic form and styling, the extruded frame members are essentially redundant. In other words, the spaceframe might as well be replaced by the intersections of the planar surfaces which must be included anyway. Research at Ford comparing mass reduction with aluminum spaceframe and unibody designs corroborates this trade-off between tooling cost and mass reduction potential for these two design categories (*ibid.*).

Aluminum also has advantages over composites because of the more extensive data and knowledge base for its application and its compatibility with some steel BIW manufacturing processes. On the other hand, there are many manufacturing-engineering challenges associated with aluminum handling, part joining, and recycling of structures made from multiple alloys, although it is projected that these obstacles will be overcome by 1997 (*ibid.*).

At around $3/kg, the current price of aluminum is about four times that of steel by weight and, even with material mass reductions and tooling cost savings, might double finished *part* costs (Gjostein, 1995a). Analysis by IBIS Associates indicates a 30% increase in manufacturing costs per *vehicle*, including materials, at a production volume of 180,000 units per year (Mariano *et al.*, 1993). The price of aluminum is typically seen as inextricably tied to smelters' electric power costs (which aren't likely to fall much in the foreseeable future) since its production is so energy-intensive. Slab casting of aluminum sheet could largely close this gap by cutting the cost *penalty* for stamped aluminum automotive parts by 60% as a result of a 30% reduction in materials cost (Sherman, 1995).

Fiber Reinforced Composites

Composites offer advantages in both vehicle design and production. High specific material strength and stiffness, along with very high fatigue resistance, allow significantly reduced mass while maintaining or even improving component strength and durability and vehicle stiffness. The engineering properties and degree of isotropy of polymer composites are controllable over a wide range (Eusebi, 1995). With proper design, specific crash-energy absorption can be two (*ibid.*) to five (Kindervater, 1994) times that of steel. Molding properties of composites provide greater styling flexibility. Assembly steps, finish processes, and tooling can be reduced by about one order of magnitude through parts consolidation and lay-in-the-mold finish coatings, offsetting or possibly eliminating material cost penalties. Current industry analysis indicates the potential BIW mass reduction using carbon-fiber reinforced composites is around 60–67% (Gjostein, 1995b). These materials are not, however, without numerous manufacturing-engineering challenges.

The BIW for the full-sized carbon-fiber composite Ford LTD built in 1979 weighed 51% less than its production counterpart (Gjostein, 1995a). This example is important because it demonstrates that such mass reductions were achieved even when the technology was considerably less well developed than it is now and with a design that was not originally intended to be fabricated from composites.

The GM Ultralite, built in 1991 by a small team in less than 100 days, demonstrates the mass-saving potential of carbon-fiber composites for a comfortable four-seater with significantly better structural stiffness than the best luxury production models. While the four-seater Ultralite is smaller than is required by the PNGV design criteria, it is relevant as a well documented effort by a major automaker to design and build an automobile based specifically on the application of composites. The body-in-white *with* closures weighed just 191 kg, as compared with 372 kg for the 1995 MY Ford Taurus. This is a mass savings of 49%. However, other exemplary four-seaters, such as Esoro's H301 hybrid with its mostly fiberglass 150-kg BIW (75% glass, 20% aramid, 5% carbon, incl. seat shells and bumpers), suggest that the Ultralite was considerably *heavier* than necessary. Furthermore, the Esoro BIW without closures, bumpers, and included composite seats weighs just 72 kg. At 45 Hz, the stiffness of the Ultralite was certainly much more than needed for handling and ride quality (B. Ochalek, GM, personal communication, March 1995)—most cars are in the low 20s, with luxury models near 30 Hz.

Composite structures can be stronger than steel at 35––67% less weight, depending on reinforcing fiber materials and processing methods. Carbon-fiber composite Indianapolis 500 racecars, from which drivers routinely walk away after crashing at speeds in excess of 200 mph, demonstrate both the incredible strength of carbon composites and the relative importance of design in crash performance. Crashworthiness for lightweight passenger vehicles, particularly those with composite-fiber structures, is discussed in more detail below under Design and Materials for Safety.

GM engineers believe that the Ultralite was overbuilt and could substitute other fibers, such as glass and aramid, to cut costs where appropriate or could use substantially less carbon-fiber composite if further mass reduction were desired (*ibid.*). Furthermore, the chief powertrain engineer for the project suggests that the mass of the two-stroke engine and off-the-shelf Saturn automatic transmission could have been reduced by 20–30% if the combined package were optimized for the Ultralite (*ibid.*). This estimate, based on driveline downsizing and use of commercially available material choices such as magnesium for the transmission case, is rather conservative in the PNGV time frame. For example, aluminum metal-matrix composite gears could cut still more mass. A lower-power *and* lighter driveline requires less structural support, and thus in turn has less structural mass to accelerate.

The principal argument against carbon-fiber composites has always been cost. After all, GM spent $13,000 on carbon-fiber composites for the Ultralite. This was, however, a very low-volume purchase of pre-preg composite, made with high-cost precursors originally intended for the aerospace industry. Prices have also come down substantially since 1991. Late 1994 bulk creel (large spool) prices for structural-grade carbon fiber (used in automotive R&D at Oak Ridge National Laboratory and General Motors) were running about $18–22/kg ($8–10/lb) (Wood, 1994; Eusebi, 1995), depending on the supplier. Current prices at the low end of this range are from Akzo Nobel's Fortafil Fibers Division (Rockwood, TN) and result partly from low-cost textile-type precursor production. Fortafil hopes to offer still lower prices with a plant expansion currently underway.

Preliminary calculations at Rocky Mountain Institute indicate that, disregarding sunk assets in current technology, carbon-fiber composite fabrication of the BIW could be cost-competitive with steel if the price were about $11/kg ($5/lb) or less. Prices are expected to be at or below that level with production of 100 million pounds per year (Prescott, 1995). Under the PNGV scenario outlined for this paper (170–196 kg BIW), with a conservative assumption of 50% fiber by weight and using 75% carbon and 25% other fibers, this would entail a volume of around 672,000 cars/yr, or about 10% of U.S. domestic passenger car production. This is a demand-pull issue: the carbon fiber manufacturers will not reach the required production scales until the market demands the fibers. After the recent loss of income from aerospace and defense contractors, the industry will probably be reluctant to expand production facilities without strong incentives.

Relatively conservative automotive industry projections for carbon fiber price reductions at the increased production volumes which would accompany *widespread* automotive use suggest prices as low as $6.60/kg ($3/lb) (Eusebi, 1995). This is well below the level at which U.S. automakers agree carbon becomes more cost-effective than steel at any production volume. These price reductions could make carbon very competitive with other structural composites as well, suggesting that traditionally cheaper materials such as fiberglass would only be used for specific applications where their physical properties were more appropriate (*e.g.,* for toughness, fracture masking, etc.), with the majority of the BIW made from carbon-fiber composites.

One of the most valuable qualities of all polymer composite materials is their potential for parts consolidation and thus reduced tooling costs. While a BIW today typically has about 250 parts with an average of four stamping tools for each, numerous composite prototype vehicles, such as the GM Ultralite, have demonstrated the potential for fabricating a complete BIW with as few as six ‘parts’ and typically fewer than twenty. In this case, however, parts may be a combination of foam cores, generic or custom inserts (pulltruded hat sections, filament-wound tubes, etc.), woven fiber mats, roving fibers and tapes, and pre-preg (including resin matrix) or formable/stampable thermoplastic versions of the various fiber forms. The preform process required for combining these composite material forms to optimize their performance and processing properties may be time-consuming relative to stamping a single steel part, but the resulting part can be very large and complex in form. While high-volume production is likely to use large numbers of tools for automated preform processes, only the dozen or so actual molding tools must sustain the relatively high pressures needed to maintain uniform part thickness. Thus the preform tools can be relatively inexpensive. With such a small number of capital-intensive tools, parallel production lines can be afforded to offset composite’s potentially slower processing times, which can in turn be improved by optical or electron-beam curing.

It could be argued that the example of the Ultralite is inappropriate, since its BIW was fabricated using hand lay-up methods. More recently, however, GM fabricated and successfully crash-tested a one-piece (foam core and a multi-stage preform process) front rail assembly as a study of processes that might be used for high volume production. The one-piece glass-reinforced composite front rail replaced an assembly of fifty steel parts (again averaging four tools per part) (Eusebi, 1995).

Not only do these advances in materials technologies make significant BIW mass reductions feasible, exceeding the 50% PNGV goal, but they can cut product cycle times and capital investment for tooling (Lovins, 1995b Lovins, *et al.*, 1995). In other words, new materials technologies may help reduce fuel consumption, emissions, *and* the risk of introducing a new model or modifying an existing one. Increased competition among materials options is already accelerating improvements in mass and manufacturing cost, even for steel parts. Furthermore, as noted earlier, an ultralight platform permits hybrid drivesystem options which would be too complex and costly for heavier, less efficient platforms. So, contrary to the notion that building ultralight automobile structures will drive new car prices up, the cost per car to the manufacturer and consumer is likely either to remain approximately the same or to drop as the automotive industry shifts to lightweight materials.

VEHICLE PLATFORM DESIGN, ROAD LOADS, AND ACCESSORY LOADS

Achieving Balance

Vehicle design is often referred to as “the art of compromise. ” However, this implies only zero-sum trade-offs without synergies. Our analysis indicates that while incremental changes in design tend to trade one desirable quality for another, less conventional options often benefit from concurrent introduction. The degree of trade-off can be more a function of design execution or extent of the shift in a parameter than a function of the parameters themselves. One noteworthy reason for placing emphasis on this platform design balancing act is that vehicle efficiency gained through reduction in road loads will also necessarily result in lower emissions per vehicle-mile, since it is not *how* fuel is converted but how *much* fuel is converted that will be affected.

Parameters affecting platform drag typically fit the balancing-act description. Achieving a very low coefficient of aerodynamic drag may limit styling options, particularly for the rear end of the vehicle. Frontal area reductions to cut aerodynamic drag can cramp interior space and limit side impact protection options. Reducing rolling resistance via a change in tire design and pressure can introduce challenges in suspension design to prevent ride harshness, and possibly degrade traction if not properly executed. Cutting curb mass to reduce rolling resistance further makes design for ride comfort even more challenging as the ratio of unsprung mass to curb mass increases. Low mass also makes collision with stationary object easier to design for, while making car-to-car involvements with heavy collision partners much more challenging. Some such parameter changes may affect production cost; others are more likely to affect engineering requirements or customer acceptance. A balance is desirable to produce a vehicle that achieves efficiency and emissions goals *and* is perceived by consumers as a *better* car than its comparably priced conventional counterparts.

If it were assumed that significant curb-mass reduction is prerequisite, independent of vehicle size, then two general strategies could be combined or implemented separately to achieve three or more times the current average fuel economy. A focus on moving the domestic family car market toward a smaller four-plus seating package (such as the very popular Honda Accord) and *much* sleeker design would further reduce curb mass and cut aerodynamic drag. This would mean departing from the PNGV design criteria, but might incur very little or even *negative* net manufacturing expense (reduced platform drag may cost less than reduced driveline size and complexity saves). Alternatively, a focus on achieving and maintaining extremely high efficiencies in drivesystem components, via very careful optimization of technology and control strategies, would convert more of the fuel energy into vehicular motion. This approach may be harder to push through in some respects because of required R&D time and expense for nearly every component. The best strategy would strike a balance between these two extremes. If all PNGV criteria are to be adhered to, however, the first general strategy becomes limited primarily to design and engineering changes, with size remaining nearly fixed.

Vehicle Configurations

The configuration of the vehicle, particularly with regard to passenger seating, affects elements of efficiency, performance, and marketability. The PNGV criteria imply, by reference to the 1995 MY Ford Taurus, Chevrolet Lumina, and Chrysler Concord as baseline vehicles for load-carrying capacity, that vehicles meeting the PNGV goal of tripled fuel efficiency must be capable of carrying up to six passengers in two rows of seats. This unfortunately rules out the significant reduction of frontal area or simply designing most models for only four occupants (and, to some degree, the reduction of aerodynamic drag coefficient that could be achieved by designing relatively long and narrow cars with three rows of two seats rather than two rows of three). Because current market trends demonstrate the high demand in the U.S. for cars such as the Taurus, Lumina, and Concord, and future market trends are difficult to predict, we model a PNGV design scenario with up to six passengers in two rows, and a further optimized scenario with just four-passenger seating.

Decoupling of Mass and Size

The use of lightweight materials for the BIW largely decouples vehicle mass from size, allowing substantial mass reductions without downsizing. This is particularly true for polymer composites, with their exceptionally high specific strength. On the other hand, this kind of thinking divorced from good whole-system design could lead to poor packaging optimization or even *increased* frontal area, offsetting some of the fuel economy and power requirement reduction gains for which the lightweight materials may have been chosen.

Mass Contribution to Peak Power Requirements

Mass is the single largest contributor to both intermittent and continuous *peak* power requirements. For this reason, mass determines the size, and cost in most cases, of all the drivesystem components. Even with a curb mass reduction of 51% from the 1995 MY Ford Taurus (as representative of the CTL benchmark), maintaining 60 mph on a 6% grade requires more than twice as much power (13.43 kW) as all other cruising loads combined for the PNGV design scenario modeled for this paper. The peak power for acceleration from 0–60 mph in just under 8.4 seconds is about 43% more still (41.86 kW). Adding 10% to the mass raises the power required to maintain 60 mph on a 6% grade by about 5% and the power required for 0–60 mph acceleration in less than 9 seconds by about 7%.

Mass Reduction

As discussed later under Modeling Results, fuel economy for HEVs may be less sensitive to mass reduction than to other variables, such as APU efficiency. The requirement for high levels of acceleration and braking performance, while maintaining reasonable component costs and packaging for electric motors, controllers, and power storage devices, then becomes a principal reason for mass reduction. The high power requirements associated with heavy vehicles may even preclude the feasible application of some energy storage options for HEVs. So while the gains in fuel economy may justify one level of mass reduction, the performance, cost, and packaging benefits may justify another, and the combined benefits still more. A cautionary note, however: excessive dependence on low curb mass for the purpose of achieving performance criteria could result in unacceptable performance losses when the vehicle is fully loaded, and in more difficult and costly corrective design for the resultant vehicle dynamics.

Although made less important by efficient drivesystems, regenerative braking, and low-rolling-resistance tires, mass reduction still contributes significantly to overall fuel economy. The direct contributions of mass reduction are lower rolling resistance and reduced power requirements for acceleration and gradability. It is important, however, to apply a systems approach to mass optimization, as the ratio of fuel economy improvement to mass reduction should be far greater than the roughly 1:2 relationship that would probably be achieved absent a systems approach.

For example, low mass contributes to fuel economy indirectly by allowing much smaller APU and electric motor operational maps for hybrid electric vehicles. The dynamic range between cruising loads and acceleration loads is compressed, enabling better optimization of component efficiencies over the entire driving cycle. The control strategy turndown ratio (ratio of peak-power to lowest-power operation) can be better matched to the range of lowest specific fuel consumption for the APU. The electric traction motors can also have a lower peak power, thus operating at a higher percentage of their peak capacity under typical non-peak loads. That translates to an efficiency gain of about 4–12 percentage points (+5–15%) depending on the motor type, design, and actual loads (Cole, 1993a).

Mass Decompounding

Because mass decompounding is non-linear and discontinuous, there is no simple calculation to describe it. GM uses a rule-of-thumb factor of ~1.5[3] for current production cars. For example, if 100 kg are saved by material substitution, then 50 kg more can be saved by downsizing the components and structure which no longer have to accelerate, carry, or stop as much mass. However, a constant factor cannot capture the more complex dynamics actually at work.

For a given vehicle payload capacity, the primary and secondary units of mass saved[4] tend to converge over recursive re-optimizations, and more rapidly once payload mass becomes a relatively larger factor than curb mass. The possible exception to this is the threshold at which mass reduction allows the economical application of a series hybrid-electric drivesystem with the potential to provide equivalent performance with fewer mechanical parts and significantly smaller components. In other words, the mass decompounding factor that relates primary and secondary units saved gets smaller and smaller (iterated over recursive re-optimizations), until absolute and specific power requirements become small enough to make hybrid drivesystems attractive (as opposed to adding mass, cost, and complexity). The decompounding factor can then rebound with hybridization of the vehicle. After that potential rebound, the primary and secondary mass savings begin to converge again.

As mentioned previously, carbon-fiber composites were substituted for steel in a 1979 Ford LTD, saving 0.75 secondary units of mass for every primary unit, yielding a factor of 1.75 (Gjostein, 1995). If the process were done just once, beginning with material substitution that cut the BIW mass by 50% and then merely downsizing other components accordingly, with no recursions, it would be difficult even to achieve the current PNGV curb mass reduction goal of 40%. If, however, material substitutions are applied to components *other* than the BIW, which in turn require less BIW structure to carry them, and the process is repeated several times, then 40% or more starts to look quite feasible.

What, then, might be responsible for the difference between the PNGV 40% goal for a pre-production prototype in the year 2003 and the roughly 50–55% (depending on size of base model used for comparison) hurriedly achieved with the GM Ultralite in 1993 with mostly off-the-shelf components?

Since the Ultralite carries only four passengers, while the PNGV goals specify up to six, the payload-to-curb-mass ratio may have a greater effect for a PNGV design. But it would take very little additional material mass simply to make the Ultralite wider (essentially slicing the vehicle down the middle and adding a 'leaf'). The two additional passengers would add only about 15% to the gross mass. If lightweight

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[3] Other automakers use a factors of 1.3–1.75. Although the exact origins of these rules-of-thumb are obscure, the relatively low payload-to-vehicle-mass ratio for heavier designs tends to tends to yield a higher factor, while *incrementally* lighter designs with the same payload capacity yield a smaller factor because the vehicle structure and drivesystem still have to support and accelerate the same load.

[4] The vocabulary is actually misleading, as the terms 'primary' and 'secondary' imply only a one-step adjustment, rather than a process of successive recursions until successive and iterative re-optimizations converge to their asymptotes.

structural materials and hybrid drivesystem components were used, the compounding of this additional mass would raise the *curb* mass by about 12%, to ~710 kg. (It should be pointed out that only mock airbag modules were installed in the Ultralite, and that additional materials or structures might be required to obtain acceptable levels of crash energy absorption.) Even these considerations and close further scrutiny of the 635-kg Ultralite do not, however, appear to justify the additional 220 kg—almost a quarter of a ton—included in the PNGV goal if both are compared to the 1,423-kg 1995 MY Ford Taurus (Lovins, 1995a). With a 0–60 mph acceleration time of 7.8 seconds, performance certainly was not sacrificed for the Ultralite; and there was still room for significant further mass optimization of everything from the BIW materials to the oversized transmission, and even the air-conditioning system (B. Ochalek, GM, personal communication, March 1995).

The systems design approach to mass decompounding may be responsible for this gap and should be carefully considered as part of the PNGV effort. Systems optimization can lead not only to downsizing of components, but also potentially to the displacement of components which may no longer be needed, saving further mass and cost.

Multiple systems optimization recursions uncover numerous linked opportunities for mass and cost savings. If, for example, less mass must be accelerated, then the output of the drivesystem can be reduced, thus reducing the structural requirements for mounting and supporting the drivesystem. The smaller peak loads also improve the feasibility of using a single fixed-ratio constant-mesh reduction gear on the output shaft of the traction motor(s) in an HEV, thus eliminating any sort of conventional multi-speed transmission. Given the reduced dynamic range of power requirements, motors which function well at low direct-drive shaft speeds, such as switched reluctance types, could even allow elimination of that single gear set. Smaller, lower-power drive components typically require smaller cooling systems, and thus less coolant mass *and* smaller air inlets, which reduce aerodynamic drag and thus drivesystem energy and power requirements, which then can be made still smaller and lighter. With a *gross* vehicle weight equal to the curb weight of today's subcompacts, power steering and power brakes could also potentially be eliminated as they were in the Ultralite, further cutting costs and improving control at higher speeds while still maintaining ease of maneuverability. Spectrally selective glazing, insulated body panels, breathable seat materials, and other design options can all reduce cooling and heating loads, thus reducing the mass, bulk, and power requirements of the HVAC system.

Along with mass savings, these options could provide substantial reduction of mechanical complexity and close-tolerance machining costs normally associated with automotive transmissions, power steering units, and possibly driveshaft and axle joints. Ultimately, the point at which mass reduction minimizes the system cost and complexity for the entire vehicle should be determined before the design is locked into any particular choice of structural materials and drivesystem components. A more detailed mass budget will follow the discussion of modeling assumptions below.

Rolling Resistance and Tires

Rolling resistance is the product of vehicle mass and the coefficient of tire rolling resistance, with the addition of small parasitic losses from wheel-bearings and brake drag. The power required to overcome rolling resistance rises linearly with vehicle speed. At 35 mph, rolling resistance is ~50% of the total road load for the PNGV scenario modeled. At 60 mph, that fraction is just 25%. Given other assumptions in this paper, a rolling resistance reduction of about 55–60% appears desirable to meet PNGV goals (Volvo claims a rolling resistance reduction of 50% using tires from Goodyear on its 1,580-kg hybrid ECC). While parasitic losses can be reduced to extremely small values by using high-quality double offset ball bearings and special mechanisms to retract brake pads consistently from the rotors, substantial reduction of tire rolling resistance is far more challenging.

Low-rolling-resistance tires for a lightweight vehicle would differ from today's mainly in quantity of rubber used, tire profile and tread design, and details of rubber compound composition. Rubber content is reduced by changes in both tire design and load requirements. Providing good performance with less mass of rubber reduces friction, and thus rolling resistance and wear. This would be possible for the PNGV scenario modeled partly because the tire would carry about 40% less load than current family sedans, even when the vehicle is fully loaded with six passengers and luggage. It would also result from improved tire design. Tire mass, including crown reinforcement materials, might be reduced from the current average of about 10 kg per tire to about 4.5 kg.

A switch from woven steel belt reinforcement to Kevlar or other aramid fiber crown reinforcement belts could save more weight while improving tire wear characteristics (M. Wischhusen, Michelin, personal communication, 16 January 1995). Aramid crown reinforcements are already used in high-performance tires where their cost can be easily recovered at premium prices. Although this might seem to present recycling concerns, Mitsubishi specifies Kevlar-reinforced tires for its HSR-IV concept car partly because they are considered *easier* to recycle than steel-belted tires.

With the introduction of its XSE tires Michelin claims to have reduced rolling resistance by 35% compared with typical replacement tires, and by 17% compared to the best original-equipment tires now specified for production vehicles, while concurrently improving all-weather performance. Those improvements required a combination of modified tire profile to reduce strain and volume of rubber subject to hysteresis (the source of rolling resistance), mass reduction (to lessen the forces that cause hysteresis), improved tread design, and a new "Smart Compound" that replaces the normal carbon black with a form of silica to maintain traction in rain and snow while cutting rolling resistance. The Michelin XSE technology recently became commercially available and has been selected as original equipment by BMW, Chrysler, Honda, and Mercedes-Benz. (*ibid.*)

Very low rolling resistance has been demonstrated by the Goodyear Momentum radial tires for Chrysler's electric van and Aero Radials used on GM's Impact electric vehicles currently under evaluation by electric utility customers in several major cities. With a rolling resistance coefficient r_0 of ~0.008, the Michelin XSE tires fall short of the 0.0048 coefficient achieved with the Aero Radials as tested by GM at 65 psi on the Impact (GM, 1990), which is what might be required to meet or exceed PNGV goals, but show promise because of their ability to maintain excellent all-weather performance. The high inflation pressures of 50–65 psi contribute significantly to the low rolling resistance for these special Goodyear tires. Properly engineered tire design and match to specific vehicle requirements can allow tire pressures in this range without sacrificing vehicle performance or safety (*ibid.*). The ride harshness that might result from high-pressure tires could probably be dealt with via good suspension design, although this gets considerably more challenging with lightweight vehicles. Some current passenger cars without active suspension already make the difference between 35 and 50 psi essentially undetectable by the occupants. Vehicle mass is in this case advantageous, as it provides a stable reaction member for the suspension system. For this and other reasons discussed below under Vehicle Dynamics, Safety, and Crashworthiness, active suspension might be necessary for lightweight vehicles. Even without high tire pressures Goodyear claims coefficients of rolling resistance as low as 0.007 for some of its *current* production OEM tires (B. Egan, Goodyear, March 1995), so achieving even lower coefficients for future tires may not necessarily be pressure-dependent.

It should be noted that the current SAE standard test procedure for rolling resistance coefficients results in slightly lower values than should be expected on concrete or asphalt road surfaces. This stems primarily from the smaller contact patch area between the tire and convex surface of the steel roller it rides on for the standard test. On the other hand, the effect of the smaller contact patch and other contributing factors (such as lower surface friction) are partly offset by the SAE test requirement that tires be run at 85% of their maximum designed load, which is seldom the case in actual use. Tire rolling resistance is thus typically about 10–15% worse in real-world condition than in standardized laboratory testing (*ibid.*). This discrepancy should be reduced by the specification of large-diameter steel rollers for the new SAE standard test.

Aerodynamics: Frontal Area

Comfortably seating one 95th-percentile adult in a moderately reclined position requires about 0.55 m^2, including headroom. Assuming the PNGV design specification that the vehicle must seat six in a sedan format (only two rows of seating), the practical limit for the frontal area of the interior space is around 1.65 m^2. While the roof and floor sections directly above the occupants' heads and below their feet need not add significantly to this dimension, the practical limit, and perhaps equally important the marketable limit, for cross-sectional area of the doors, including side-guard beams and interior bolsters for side impact protection, is probably close to 0.1 m^2 each. A slight curvature of the roof between outboard seating positions may add another 0.1 m^2. Thus, including body skin thickness, an appropriate baseline dimension for frontal area would be 1.95 m^2, which is about 0.18 m^2 less than the 1995 MY Ford Taurus. This figure will be assumed for modeling the PNGV design scenario in this analysis. It is assumed that the advantages of packaging improvements and more compact structures to prevent side impact intrusion may be used up by improved side impact protection and increased interior space, if such vehicles are to be introduced at the high end of the market. A smaller frontal area of 1.85 m^2 may be appropriate for economy models, which carry up to six passengers, but with less interior space and still thinner door sections.

Well packaged prototypes such as the Esoro H301, GM Ultralite, and Renault Vesta II, with respective frontal areas of 1.8 m^2, 1.71 m^2, and 1.64 m^2, have relatively upright, comfortable seating for four adults. Based on these vehicles, the assumed practical limit of frontal area for the further optimized 4–5 occupant design scenario modeled is 1.75 m^2. Clearly some *four-seat* models could be made smaller than this (*e.g.*, 1.6–1.7 m^2), but because the U.S. market may require more packaging flexibility, such as space for three adults in the rear seat for short trips, a 1.75 m^2 frontal area and 4–5 occupant seating has been chosen as generally representative of well optimized sedans within the scope of the PNGV.

Aerodynamics: Drag Coefficient

Aerodynamic drag, which varies as velocity cubed, is by far the largest load at highway speeds on level ground. For an average 1995 model cruising at 60 mph or more, aerodynamic drag typically consumes well over twice the power of rolling resistance. Given the previously discussed limits of frontal area, lowering the drag coefficient (C_D) is the principal means of reducing this load. The C_D results from the combination of form drag, interference drag, induced drag, surface drag, and internal flow drag.

This is one design element which appears to be underemphasized in current PNGV literature. It may be partly because prototype vehicles developed in the past decade or so suggest the level of improvement which can be obtained, and further work may be seen as largely vehicle-specific. There does not, however, appear to be sufficient justification for the rather pessimistic initial example, in the PNGV Program Plan and subsequent discussions, of just 20% lower aerodynamic drag, with only a mere suggestion that such parameters should contribute to the success of the program. One advantage of focusing more effort on lowering the C_D is that its marginal cost per car can be negligible, depending on the design, if drag is taken into account early in the design process.

Form drag is primarily a function of how well the shape of the vehicle parts and re-assembles the airflow without excess turbulence. In general this leads to vehicles with a well radiused nose (which can be flat or even concave, as long as edges are rounded to prevent eddies), a noticeable taper towards the rear, and well defined trailing edges to minimize turbulence in the wake. Many current production models include modest tendencies toward this general form, but are still quite far from what is required for drag reductions of 20–40%. The principal limiting factors for form drag are styling and the ratio of vehicle length to cross-sectional area.

Interference drag is caused by mirrors, wheels, drivetrain components, and body seams which physically protrude from the basic form and trip the airflow. Air fences which result from air exiting relatively high-pressure zones, such as the cabin interior, into high-velocity low-pressure zones trip the airflow as well. Air fences result from leaking door, hood, and window seals, poorly placed exit vents, or unconstrained airflow exiting from the engine compartment. While most production cars show increased attention to upperbody seams, seals, and vents, there is much room for improvement in mirror fairings, chassis component form and placement, treatment of underbody edges, and flow control of air exiting from the engine compartment. BEVs and HEVs have the advantage of fewer and smaller components, such as transmission, drive shaft, and exhaust system, which might make smoothing the underbody more difficult in a conventional automobile.

Induced drag results from a pressure differential on opposing sides of any portion of the vehicle. It is typically a product of form drag and interference drag, which may increase the pressure under the body (for example, by tripping the flow with body edges, chassis components, and air fences) while speeding the flow over the top of the body by forcing it to take a longer but smooth path. The result, in this case, is upward lift, just as with an airplane wing. Automobiles are of course not intended to fly, so this is wasted energy. (The one exception to this is the use of downforce, or downward lift, in high-performance cars to improve traction at high speeds.) With very little attention paid to reducing underbody turbulence, most production cars have significant lift-induced drag. Rather than smooth the underbody and attempt to tuck chassis components up out of the flow, the industry strategy has tended towards air dams below the front bumper to force much of the flow around the vehicle rather than under. This needlessly increases frontal area and leads to the erroneous notion that achieving very low aerodynamic drag requires extremely low ground clearance[5].

Surface drag is caused by skin friction, and typically produces non-stall turbulent flow immediately adjacent to the vehicle's surface beginning about 20–30 cm back from the nose. Special surface treatments developed for aerospace and marine applications could potentially be applied for passive control of this boundary layer effect. This would depend on marketing textural surfaces somewhat akin to the coarse matte finish which is common on polymer casings for many small consumer products. Although there are no experimental data for automotive applications of drag-reducing surface finishes, it is likely that such an approach could contribute to a much lower C_D than would otherwise be practical, since it would have no effect on functionality and may even lower the cost of finishing the body panels.

Internal flow drag is a *product* of air intake volume and efficiency of flow through the various paths. Internal flow paths designed to minimize turbulence are clearly beneficial. Less obvious is the reduction of cooling and combustion air intake volume associated with the more efficient drivesystems of BEVs and HEVs, and with reduced road loads due to better platform design optimization.

If functionality and efficiency are the primary requirements, the practical limit for the C_D may be around 0.15–0.18, but substantially lower with advanced passive (and possibly active) boundary layer control and virtual form modification through advanced flow control. Several recent prototypes, including the GM Ultralite, GM Impact, and Renault Vesta II, all have a C_D around 0.18–0.19. The PNGV criteria actually make achieving a C_D in this range easier in some respects, as the elements which cause interference drag are physically smaller relative to the frontal area for a mid sized car than for these smaller prototype vehicles. The fully functional Ford Probe IV[6] prototype four-door sedan demonstrated a C_D of 0.152 in full-scale wind-tunnel testing at Lockheed (Howard, 1986). If market acceptance and stylistic variations for product differentiation take precedence, however, the C_D could be pushed back up toward 0.20.

[5] If chassis components are streamlined or otherwise covered by a smooth floorpan to prevent interference drag, there is little reason, beyond the limited exposure of more of the tires' frontal area, to prevent the airflow from passing under the car (P. MacCready, AeroVironment, personal communication, April 1995). Allowing the airflow to pass under the car can actually aid in eliminating lift-induced drag.

[6] The 1985 Ford Probe V concept car achieved a C_D of 0.137 (Howard, 1986), but was not as close to meeting PNGV criteria as the Probe IV and used active aerodynamic features that might have significant fuel-economy, cost, and complexity penalties.

Glazing and Accessory Loads

The careful integration of technologies that are commercially available in similar or adaptable forms can cut the fuel, weight, and cost penalties of interior heating and cooling (hotel loads) by an estimated 75% or more. This is based on Rocky Mountain Institute's analogous experience with super-efficient building (Houghton, *et al.*, 1992) and on documented automotive thermal management experimentation at Lawrence Berkeley Laboratory (Hopkins *et al.*, 1994), and is agreement with HVAC equipment re-design at Arthur D. Little, Inc. (P. Teagan, A.D. Little, personal communication, June 1995).

Spectrally selective, and possibly angularly selective, variable-selectivity, or electrochromic, gas-filled thin double-glazed windows and insulated foamcore body panels could minimize unwanted solar heat gain and help retain interior heat on cold days. PPG's Sungate 'solar-control' glazing reduces infrared and ultraviolet influx and is available in the U.S. for automotive applications. Thin double-glazed windows are already used on European luxury sedans to reduce interior noise levels. Laminated spectrally selective glass is being produced in Germany under a Southwall license for Mercedes.

Spectrally selective glass rejects infrared and ultraviolet rays that would otherwise heat the interior, cause glare, and degrade interior surfaces. This glass is not tinted; it allows nearly all of the visible spectrum to pass unimpeded (Hopkins *et al.*, 1994). A solar-powered ventilation fan should also be included to exhaust excess heat when the vehicle is left sitting in the sun (*ibid.*). Accessory load reduction by such means could be an economically appropriate limited use of photovoltaic cells for mass-produced vehicles. Stylistic flexibility would be maintained, as the small panel of cells could easily be flush-mounted, integral to the roof or rear deck.

Coated plastics, such as acrylics, polycarbonates, or other high-refractive-index polymers, could reduce weight and cost as replacements for glass. Plastic glazing could provide the same spectral selectivity as glass at half the weight and lower cost, with better thermal insulation, impact resistance, occupant retention in collisions, and stylistic flexibility. Recent advances in protective hard microcoatings, including silica, alumina, and even diamond, have boosted the potential for plastic glazing in automobiles. (Harbison, 1993)

Safety concerns are being successfully addressed through testing of bi-layer polymer/glass glazings at GM, DuPont, and elsewhere. In laboratory impactor tests, polyurethane/glass and polyester/glass bi-layer windshields weighing 30% less than conventional windshields have demonstrated lower initial peak forces and slightly elevated but acceptable secondary forces and head injury criteria (although with greater statistical variation than conventional windshields that were "hand picked" for testing by the manufacturer) (Browne, 1995).

Potential 75% reduction of cooling and heating loads would downsize space-cooling and air-handling equipment and the energy sources needed to run them. A very small variable-displacement, rotary-vane, or electric-turbine compressor or heat pump with nylon (USMC, 1994), rather than aluminum, heat exchangers, or even possibly a desiccant/indirect-evaporative system driven by APU waste heat, could replace the bulky and power-intensive air conditioning systems common today. The HVAC system developed by Nartron Corporation (Reed City, MI) works at less than one-tenth of typical automotive AC system pressures, allowing it to be made almost entirely of plastics, including the high-speed turbine compressor. It weighs only 16 kg for a 1.43-ton (5.03-thermal-kW) cooling output, and would weigh a fraction of that when sized for 75% lower cooling loads. The Nartron unit is self-contained, has only one moving part, uses a non-CFC refrigerant that is liquid at ambient temperature (so it won't evaporate into the atmosphere if there is a leak, and can easily be drained out for servicing or refrigerant recovery), and weighs about as much as just the compressor in a typical automotive HVAC system. Both Ford and Chrysler have contracted with Nartron to design such systems for use in some models, starting in 1996 (Gawronski, 1992).

Heating loads could be cut by the use of foam-core materials for the BIW (or insulation if the body were aluminum) and by the insulative properties of the added foam occupant protection bolsters and possible gas-filled selective windows. For reduced internal flow drag, cooling systems for the APU, motor(s), and controllers should have ducted airflow which could be selectively redirected to the passenger compartment for heating. A positive-temperature-coefficient ceramic heater core could provide supplemental heat when the APU was not warmed up or otherwise in use, as the highly efficient electric drivesystem components would give off very little waste heat.

CRASHWORTHINESS, SAFETY, AND VEHICLE DYNAMICS

Design and Materials for Safety

Lightweight vehicle design, while presenting new challenges, does not preclude crashworthiness and could even improve it under some conditions. Lightweight design also improves maneuverability and stopping distance, allowing the driver to avoid many potential collisions. Using proven technologies for energy absorption, force-limiting occupant restraints, and rigid passenger compartment design, even ultralight vehicles can surpass the safety of today's cars in many types of collisions. The possible exceptions to this are high-speed head-on collisions with, and side impacts from, a significantly heavier collision partner, though these might be effectively dealt with through innovative and careful design.

Frontal Impacts

Low mass vehicle design for frontal impacts must provide acceptable rates of occupant acceleration for many different levels of force. This is the result of both high ratio of gross mass to unladen curb mass and the increased potential for collisions with a much heavier moving vehicle.

Designing for frontal collisions with fixed objects, for a given payload, is relatively straightforward. The car need only absorb its own kinetic energy (including that of the payload) at a rate survivable for the occupants. The available crush stroke must be long enough to absorb energy at that rate for the highest anticipated speed of impact. If the total available crush stroke is longer, then it can be designed to crush more easily, reducing the rate of deceleration of the occupants.

The problem becomes considerably more complex when a change in the payload is significant relative to the curb mass. For an ultralight vehicle, this may mean as much as doubling the mass at maximum gross vehicle weight. The total kinetic energy would be increased proportionately. If the mass were doubled at gross vehicle weight, then the crush zone would have to either be twice as long to absorb twice the energy, which would very likely be impractical, or twice as stiff to provide the same rate of energy absorption as it would at half the gross vehicle weight. A second stage of crush stroke, much stiffer than the initial stage that is designed for fixed barrier impacts at low payload level, might be required. There might also have to be a transitional zone to avoid severe acceleration spikes. Thus the crush stroke for a lightweight vehicle may have to be much longer than is typical for conventional cars in order to allow for fixed barrier impacts over a wide range of gross vehicle weight. Alternatively, occupant restraint systems could be relied upon to provide controlled ride-down within the passenger compartment, augmenting the capability of the exterior crush zone. Combining these approaches may be necessary to manage the even greater range of kinetic energy levels involved in car-to-car collisions, as discussed below.

Only 3% of all car-to-car involvements are head-on collisions (National Safety Council, 1991), and only a fraction of those are at high speeds. This, however, is not a justification for avoiding the challenges of designing for high-speed collisions with heavier cars—a goal that may be achievable with careful design for collision partners of twice the mass or more. As discussed below, this has already been demonstrated for ultralight *and* very compact vehicles at low speeds. Frontal impacts in general are the cause of roughly 32% of all passenger car fatalities (Riley, 1994). This suggests that even today's relatively heavy steel cars do not fare well in frontal impacts, even with stationary objects. The latter, as noted above, is easier to design for in vehicles of a given size but lower mass, since there is less kinetic energy to be absorbed and more space that can be devoted to absorbing it (the smaller drivesystem required for lightweight vehicles leaves more room for energy-absorbing materials). The most important challenge that must then be addressed is designing for a wide range of collision types and impact speeds, including head-on collisions with heavier vehicles.

It might be noted that building cars which cannot deal with a small fraction of potential collisions is no less moral than building heavy cars which, like trucks, are a menace to lighter vehicles of all types in terms of both momentum transfer upon impact and ability to stop or maneuver quickly to avoid a collision. Unfortunately, car design is driven more by insurance claims than morality, so lighter cars are forced to compensate for the menace of heavier cars.[7]

If, for example, a 1,400-kg car and a 700-kg car were to collide head-on at 60 km/h, slowing the heavier car to 20 km/h and forcing the lighter car to change from 60 km/h in one direction to 20 km/h in the opposite direction, the changes in velocity (Δv) for each would be 40 km/h and 80 km/h respectively. While the difference in Δv for the two cars in this scenario is proportional to the difference in mass, the scenario depends on either the smaller car's absorbing most of the kinetic energy dissipated in the crash or forcing the heavier car to do so. The former has practical limitations in terms of the amount of available crush-space in a given car. The latter could be accomplished by making the front of the lighter car extremely stiff, but that is in direct conflict with the required crush rate for collisions with stationary objects. In other words, the front of each car has to be soft enough to crush at a rate survivable by the occupants, given the capabilities of force-limiting occupant restraint systems, in the event of a full frontal impact with a fixed barrier.

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[7] As a matter of policy, it might make sense to require heavy vehicles to have large and relatively soft energy-absorbing crush zones (limited of course by volume and by the need to absorb their own kinetic energy in collisions with stationary objects) to extend the event duration, and thus reduce the acceleration of the lighter vehicle in a head-on collision.

The best approach may be to combine these two techniques with a soft initial crush stage for fixed-barrier impacts. The soft initial stage would absorb most of the kinetic energy of the lighter car, followed by successively stiffer stages to absorb as much energy as possible from the heavier car, and finally a rigid belt-line around the passenger compartment, forcing the heavier car to crush as much as possible.

Some of the means by which this might be accomplished have been demonstrated in head-on collisions between a very compact 522-kg fiberglass Horlacher vehicle and a 1,259-kg Audi 100. The Horlacher vehicle used a rigid belt construction to force the larger vehicle to crush, and used interior space and restraint systems to provide occupant ride-down. While the fixed barrier crash of the same vehicle at an impact speed of 9.1 m/s (20.4 mph) yielded a Δv of 9.2 m/s and maximum vehicle acceleration of 84 *g*, the head-on collision at an impact speed of 14.5 m/s (32 mph) resulted in a Δv of 14.5 m/s and maximum vehicle acceleration of 54 *g* (Niederer, *et al.*, 1993). Photographs show the 522 kg Horlacher as having remained very much intact, with only a flattened front end and shattered windshield. This is largely due to the rigidity of the ~10-kg foam-filled fiberglass impact beam which wraps around the vehicle and is capable of withstanding ~0.25 MN force. It should be noted, however, that the impact speed for the Audi 100 was just 16 mph (half the speed of the Horlacher). The level of damage and maximum Δv for the lighter vehicle would have been much higher if the vehicle speeds had been equal. Still, this demonstrates the effectiveness of rigid composite-fiber structures in forcing heavier and larger vehicles to crush (given a reasonable crush zone in the larger vehicle).

More crush zone on the front of the light vehicle could lower the peak *g* loading in fixed barrier crashes, and absorb some energy from the impact of a heavier vehicle. If enough space were devoted to crush stroke, along with more than the usual occupant ride-down via the restraint system (also demonstrated by the Horlacher vehicle), the crush zone could be staged to provide variable energy absorption. As mentioned above, this might include an initial very soft zone for fixed barrier impacts, followed by progressively stiffer zones to absorb as much energy as possible from a heavier or faster oncoming vehicle, and backed by an extremely rigid passenger compartment, both as a reaction member and to force the other vehicle to crush as much as possible. The result would be analogous to using the hard-shelled Horlacher vehicle as a passenger compartment, and adding the crush zones of a larger car to either end, greatly increasing the effective crush stroke. (With interior bolsters and restraint systems, the vehicle would be similar to an oversized padded crash helmet[8] with the addition of large deformable exterior cushions.)

The experimental Viking Six vehicle built at Western Washington University's Vehicle Research Institute shows the effectiveness of combining a rigid passenger compartment structure and crushable nose section in an ultralight (600-kg curb mass and 193-kg BIW with closures) vehicle with an aluminum monocoque chassis and fiberglass body skin. The Viking Six completed a 41.2 mph (18.4 m/s) fixed-barrier crash test at Sandia Labs with just 4 mm maximum passenger compartment deformation and 483 mm static crush of the aluminum-honeycomb-filled nose section. Head injury criteria and peak chest and femur *g* loading were well below FMVSS 208 injury criteria limits (Seal and Fitzpatrick, 1982). Much like the Horlacher vehicle, a rigid belt (in this case a combination of hat sections and sheet aluminum structures filled with honeycomb) was used around the passenger compartment. Viking Six was among the earliest applications of safety belt force limiters—a Fitzpatrick Engineering innovation currently under development for production vehicles.

Specific energy absorption in complex structural composite-fiber parts has been confirmed in crash tests at more than twice that of the same structure made from steel (Eusebi, 1995). Dedicated energy-absorbing, mass-producible, simple, small, conical carbon-fiber composite structures have demonstrated specific energy absorption of 100–110 kJ/kg, or about five times that of steel and three times that of the best aluminum energy absorption structures (Kindervater, 1994).

Composite structures of this type could be used to predictably absorb energy predictably, like aluminum honeycomb, but with much less mass and bulk. Non-directional materials such as polypropylene and aluminum foams could be used to supplement directionally oriented structures for oblique impacts. Even if compact energy-absorbing structures are utilized, however, crush stroke length must still be long enough to decelerate the occupants at a survivable rate. The crush stroke will need to be considerably longer than is common in compact cars if an ultralight vehicle is to absorb any significant portion of the kinetic energy from a heavier collision partner, while also maintaining a soft enough leading section to crush at a survivable rate when hitting a stationary object. Crush stoke optimization could take advantage of the space made available by largely decoupling size from mass and by the smaller and more modular underhood components afforded by a low-mass HEV (heavier vehicles would need more powerful, and thus bulkier, drive-system components).

Side Impacts

Side impacts, which are not handled very well by most conventional vehicles, will be at least equally challenging to design for in ultralight vehicles. About 30% of passenger car crashes involve some form of side impact (AAMA, 1994), which account for approximately 25% of all serious-to-fatal passenger car collision-related injuries (Lundell, *et al.*, 1995).

Conventional wisdom asserts that it would be effective simply to place a very stiff member in the beltline region of the door to limit side impact intrusion, while also maintaining sufficient vehicle mass to minimize momentum transfer from a striking vehicle. Recent research (Hobbs, 1995) suggests both that there are actually benefits associated with some degree of low vehicle mass and door designs which are not particularly rigid or, especially, do not concentrate stiffness in a small area such as a side impact beam, *and* that stiff overall side structures are needed to reduce the velocity of intrusion in car-to-car impacts (Lundell, *et al.*, 1995). The former conclusion is certainly counter-intuitive, considering that, for a given mass of the striking vehicle, the momentum transfer to the vehicle which receives the impact will increase if its mass is reduced, thus increasing the acceleration of the occupants. On the other hand, when the occupant strikes the door interior, injury will be reduced if the door has bounced away from the struck object or striking vehicle. In other words, the door will be a softer barrier if it isn't backed up by an outside object. Clearly the occupants of a very heavy vehicle with a very stiff side-guard beam would experience little acceleration as the striking vehicle was forced to crush. If the two vehicles are of

[8] Motorcycle and auto-racing crash helmets typically have an aramid-reinforced polymer composite shell with polyurethane or polypropylene energy-absorbent foam padding.

the *same* mass, however, this is no longer true. In this case there will be sufficient momentum transfer to increase significantly the importance of the effect of the door as a barrier or moving object with which the occupant collides. It is therefore desirable to strengthen the door and its aperture in a manner that avoids a concentration of stiffness adjacent to the occupants, particularly at or above the pelvis. Relatively low vehicle mass may also be helpful to the extent that it allows the vehicle to bounce slightly away from the object of impact before the occupant collides with it.

Strengthening of the entire door aperture, “B” pillar (if any), and door section below the occupant’s pelvis could help limit intrusion without presenting an extremely rigid barrier adjacent to the occupant’s torso. Such a design would, however, probably have to include some kind of crumple zone in the floor or at the base of the “B” pillar so that the base of the door system would be allowed to translate inward as a complete unit, rather than having the door tilt inward at the top. Any strengthening above the occupant’s pelvis should be well distributed and possibly even designed to be effectively less stiff when struck from the inside of the vehicle (*e.g.*, like a bridge structure that resists downforce, but could easily be lifted). Unfortunately, there isn’t room for a sufficient crush stroke in the door to decelerate a striking vehicle completely, except if its mass or speed were *very* low. Properly applied energy absorption materials might, however, be used both to distribute loads evenly and to reduce intrusion, while somewhat reducing the rate of occupant acceleration. Low-density phenolic foam door bolsters and “B” pillar design to maintain a vertical door intrusion profile have exhibited better performance in reducing chest injury from side impacts than the conventional approach focused on simply limiting intrusion (Hobbs, 1995). Volvo estimates that combining door aperture and lower door section stiffening with a seat-mounted side-impact airbag system will reduce serious-to-fatal chest injuries by about 40% for its vehicles (Lundell, *et al.*, 1995).

General Safety Feature Considerations

For composite vehicles, interweaves or overlays of aramid (Kevlar) or similar fibers could be used to control fracture propagation and shard intrusion around the passenger compartment (although this requires design attention to recycling considerations). Polypropylene, polyurethane, or low-density phenolic foam bolsters could be used on the dash and knee-restraint panels, door panels, B and C pillars, and seat backs, much like the crash-helmet padding previously discussed. Restraint systems could include front and side-impact airbags for all passengers (included in the mass budget) and pretensioning seatbelts with force limiters. While this extensive use of airbags might, based on past technology, seem to add considerable weight, recent developments in airbag technology indicate otherwise. Morton’s complete driver’s airbag modules for a car with reasonably long crush stroke (thus slower bag deployment) weigh just 1.2 kg. Takata’s newest modules are about 40% smaller and 30% lighter than standard systems, and have the added advantage of using a non-toxic inflator propellant in place of sodium azide. Passenger front airbag modules would be about twice the size and weight of the driver’s module, while rear passenger modules would be only slightly larger and side modules would be slightly smaller. A self-collapsing spread-aluminum (mesh) steering column section could allow more ride-down space for the driver. This torsionally stiff steering column design was used in the Viking Six crash test, and was actually crushed by the mass of the steering wheel, without any contact from the test dummy (Seal and Fitzpatrick, 1982). Non-spill polymer fuel tanks, such as are used in racecars, and impact-triggered electrical system disconnects could reduce the risk of fire or electrical shock.

Mass Distribution and Vehicle Dynamics

In general, low vehicle mass improves handling agility. This is beneficial both because nimble handling is a marketable trait and because it improves the potential for collision avoidance. On the other hand, mass distribution would vary considerably with payload location, resulting in widely varying vehicle dynamics.

The key to good handling may be to take full advantage of the modular characteristic of hybrid drivesystems to locate most of the mass very low in the vehicle. Lightweight BIW materials also facilitate a low center of gravity, since very little mass will be concentrated in the upperbody structure. Active suspension with independent sensors and actuators for each wheel may be necessary to maintain vehicle attitude and provide load-specific spring-rate and stiffness distribution.

Maintaining ride comfort may be one of the limiting factors for sprung mass reduction, particularly when the vehicle is lightly loaded. The design must have a low enough ratio of unsprung-to-sprung mass to allow the sprung mass to act as a reaction member for the suspension. Active suspension systems could provide a stiffer ride at high speeds, where bumps are likely to be minimal, and softer ride at low speeds. Minimizing the mass of the wheels, tires, brakes, and the unsprung portion of the suspension system would also help.

High tire pressures for low rolling resistance require more of the suspension if ride comfort is to be maintained. Well engineered, but not active, suspension systems already in use on production cars can make the difference between 35 and 50 psi tire pressure essentially imperceptible to the occupants (B. Egan, Goodyear, personal communication, March 1995).

Active suspension need not be energy-intensive if designed to be regenerative. It also might add little cost and mechanical complexity if thermochemically expandable polymer actuators are used, such as those being developed by TCAM Technologies, Inc. (Eastlake, OH).

Suspension and Steering

Continuous-fiber composite materials, being inherently anisotropic, are ideally suited for suspension components. Carbon-fiber composites would be most appropriate for control arms and other connective elements, where strength and stiffness are most important, while glass-fiber composites, which are less brittle, could be better for springs, where continual flexing is required. Both are superior to steel in these applications.

In 1977 the first transversely mounted glass-fiber-composite leafsprings—the 3.8-kg Corvette rear spring—replaced two longitudinal multileaf steel springs weighing a total of 18.6 kg, cutting spring weight by 80%. The composite leafsprings also "improved the standard of comfort by providing a more silent and smoother ride, and the useful life of the springs was substantially extended" (Therén & Lundin, 1990). Similar fiberglass leafsprings have since been used on other models, typically saving around three-fourths of spring weight in cars and two-thirds in trucks (*ibid.*). Testing in heavy trucks by GM and Shell Oil demonstrated five times the durability of steel springs in terms of lifespan under heavy use; widespread use in full-sized racing stock cars showed doubled life and graceful failure (usually a longitudinal split allowing the car to limp home) (N. Strand, personal communication, 20 January 1995). The advantages of the material for this use come from its fourfold lower density, ability to store more elastic energy per unit volume than spring steel, better vibration damping properties, and increased comfort through lower unsprung weight (Therén & Lundin, 1990).

Hub carriers, or uprights, have numerous machined surfaces, and thus might be most cost-effective to make from cast aluminum. Since the casting and machine processes for aluminum are broadly similar to those for steel, this may require little shift in manufacturing technology.

Because the fully loaded vehicle mass would be about half that of a typical car, the steering components could be significantly lighter without compromising safety. Furthermore, the steering rack housing, lower portion of the steering column, and tie rods to the hub carriers could all be made from standardized, filament-wound carbon-fiber tubing to save still more weight. With the recent development of reinforced polymers and metal-matrix composites for transmissions, even the rack-and-pinion gears could be polymer, saving both weight and cost.

Brakes

In addition to regenerative braking by the traction motors, an ultralight hybrid would require friction brakes for:

- panic stops, which would otherwise require the excessive oversizing of motors and electronics;
- absorbing braking energy in excess of LLD capacity when descending long steep grades;
- emergency backup in the event of an electronic failure;
- legal requirements;
- parking and starting on hills; and
- to drop quickly from ~5–8 to 0 mph at the end of each complete stop in urban traffic after most of the vehicle's kinetic energy has been absorbed by regenerative braking.

Assuming a curb mass reduction of 50–55%, friction brakes sized for the anticipated maximum passenger and cargo payload could be roughly half the size and mass of conventional automotive brakes, even if made from steel. However, lighter materials are desirable both for vehicle mass reduction and for reduction of unsprung weight.

Carbon/carbon-silicon carbide composites (66% carbon and 33% silicon), with 25% of the density of steel, nearly twice the temperature range, and up to twice the coefficient of friction (particularly when the brake rotor is wet), could cut brake rotor mass by another 75% and reduce size by nearly 50% again. Carbon-carbon composite brake rotors, produced mainly by Bendix and Hitco in the U.S., are commonly used in aircraft and racecars where costly materials are easily justified. High energy and furnace costs, as well as slow manufacturing processes with numerous steps, are primarily responsible for the high price of carbon-carbon composite brake rotors. The development by DLR Stuttgart, the German Aerospace Research Establishment, of a two-step process for the production of carbon/carbon-silicon carbide composites, using fast one-shot pyrolysis followed by one-shot liquid silicon injection, cuts both cost and manufacturing cycle time substantially, which may make these materials cost-competitive for lightweight production automobiles (Krenkel, 1994).

Wheels

Low sprung mass and the possible location of electric motors in the wheel hub assemblies could demand ultralight wheel construction to minimize unsprung weight, which might otherwise cause ride harshness. Wheels also need to be extremely stiff to ensure accurate and predictable maneuverability. Carbon fiber, with its superior stiffness and strength-to-weight ratio, could be the material of choice for this application. Lightweight fiberglass-composite wheels have already been produced by Chrysler as optional equipment for the Shelby CSX. Ultralight carbon-fiber composite wheels developed by the Vehicle Research Institute at Western Washington University weigh just 2 kg each (M. Seal, VRI, personal communication, April 1994)—less than half the weight of the 3.9-kg Alcoa forged-aluminum wheels used on the GM Impact BEV (General Motors, 1992). These wheels were fabricated using rather crude hand lay-up and vacuum-bagging techniques, and thus may not have been well optimized for mass, performance, and durability. Nonetheless, they were successfully tested with the Viking 21 kludge on mountainous dirt roads. With its steel chassis and 220-kg battery pack, the Viking 21 weighs more than 900 kg, so this is a good indication of the durability of ultralight carbon fiber wheels, although further testing and analysis are still needed, especially of catastrophic failure modes[9]. For our modeling mass budget, we assume 3 kg per wheel to allow for the use of carefully optimized aluminum or magnesium wheels, such as the Alcoa wheels mentioned above.

[9] One possible improvement might be molding the carbon-fiber composite material around a magnesium skeleton: the carbon fiber could provide the required stiffness while the magnesium could prevent catastrophic failure under unusually harsh driving conditions.

OTHER PLATFORM DESIGN DETAILS

Interior Trim, Carpet, and Seats

Most of the underlying shapes of the interior could be integral to the body-in-white molding and hence would need no further supporting materials except for surfaces which should be padded to reduce the risk of injury in a crash. Carpets could be lightweight hollow-fiber synthetics, such as those developed by Toyota, which are ~30% lighter than typical automotive carpeting. If composites were used for the BIW, acoustic and thermal performance could be largely designed into the foamcore of the structural monocoque shell, rather than added onto it afterwards. In the case of an aluminum BIW, jute or similar materials would be used.

Seats could use extremely lightweight but strong and comfortable ventilative mesh surfaces (as in GM's Ultralite or Herman Miller's Aeron "pellicle" office chair) supported by a tubular magnesium or polymer-composite frame. (Some existing seats using magnesium frames weigh only 7 kg each including adjustment mechanisms.) The rear seat structure could be at least partially integrated into the body-in-white, depending on fold-down features.

Lights, Electricals, Instrumentation, and Controls

Most power requirements for a passenger vehicle could be reduced by factors ranging from 3–5+ for lights to 4–8+ for ventilation to 10+ for many electronic systems. (For example, most entertainment systems still use inefficient kinds of microchips and no power management—unlike the sophisticated but low- or negative-cost hardware and software measures used to prolong battery life in modern portable units and in portable computers.) Like a modern aircraft, sensor and control signals could flow through featherweight multiplexed fiber optics, rather than wires. Optical fibers could also distribute major light fluxes, such as headlights, from two superefficient pea-sized metal-halide lamps (one spare and one operating on 35 W or less). From electroluminescent panel lights (used in GM's Ultralite) to loudspeaker supermagnets (used in Ford's Taurus), meticulous attention to detail can cut accessory and auxiliary electrical loads by at least half and possibly by tenfold.

DRIVESYSTEM

Emerging motor and power electronics technologies are making efficient electric and hybrid systems possible as never before. Those technologies are also enabling emerging APU technologies, such as gas turbines, Stirling engines, thermophotovoltaic burners, and fuel cells, which aren't well suited for conventional applications, but must be accompanied by highly efficient electric drive components. Most of these technologies have been around for decades, but until recently were not sufficiently well developed or were not enabled by other key technologies for automotive applications. There are clearly numerous engineering challenges yet to be overcome, including cost for power electronics and for many of the more recently developed APU options.

Hybrid Drivesystem Configuration and Design Trade-Offs

As discussed in relation to conventional and pure-electric vehicles, a hybrid drivesystem can be of either series or parallel configuration. In a parallel HEV the wheels are mechanically driven by the APU at least some of the time. In a series HEV the APU is used to generate electricity onboard and has no mechanical connection to the wheels. The challenge is to balance APU efficiency, APU emissions, LLD life, and vehicle cost and performance.

Parallel Hybrid Drivesystems

Parallel HEVs can tend towards mechanical complexity, typically maintaining that of conventional vehicles by trading a multi-speed transmission for one with multiple input shafts or some sort of four-wheel-drive arrangement. There is, however, at least the potential for using only a single constant-mesh fixed-ratio gear set for each input shaft. This would be contingent upon a control strategy that runs the APU only at high enough vehicle speeds to allow a single fixed gear ratio, increasing the dependence on battery range for urban driving and re-introducing some of the problems of BEVs. As discussed previously in relation to BEVs, heavy energy storage devices may preclude meeting PNGV criteria because the compounding of mass and bulk requires larger and more costly high-power components to maintain adequate performance.

If, however, advanced batteries with high specific energy (such as the lithium-based types described later) are successfully developed, a parallel configuration might be ideal inasmuch as efficiency-robbing energy conversion stages are minimized. A combined-mode control strategy, operating as a BEV at low speeds and a power-assist for high-speed accelerations and cruising, might best take advantage of the parallel configuration. If the APU operated only at highway speeds it wouldn't have to follow urban transients, although this might require a manual "shift lever" to avoid frequent on/off APU cycles that could result from vehicle speed variations close to the mode-change threshold. In "urban mode" the car would be a BEV. In "highway mode" the APU would be the primary means of propulsion, but sized only to meet gradability requirements. The electric drive would then be used as a power-assist for hard accelerations and regenerative braking.

Series Hybrid Drivesystems

Purpose-built series HEVs can actually be less mechanically complex than conventional vehicles, particularly with a solid-state APU (fuel cell or thermophotovoltaic burner). Even with a mechanical APU, the multi-speed transmission can be eliminated and the starter and standard alternator replaced by a single alternator, which either is larger or operates at much higher speeds depending on APU technology. (A gas-turbine APU, for example, could have just one moving part, including the turbine, compressor, and a very small high-speed alternator all on a single shaft.) If multiple traction motors are used, the differential and possibly even drive axles can be eliminated (depending on inboard or outboard motor location). Since electric motors are mechanically quite simple, manufacturing expenditure on close-tolerance machined parts can be less than for conventional drivesystems.

At first it may appear that a series hybrid drivesystem has only the advantage of regenerative braking, but all the disadvantages of multiple stages of energy conversion when compared to conventional systems. Quite the opposite is true. The energy conversion penalties, as an isolated variable, only exist to the degree that the product of those conversions is less efficient than the product of a conventional multi-speed automatic transmission and torque converter, jointed drive shaft if front-engine/rear-wheel-drive, and possibly even differential (if the HEV uses more than one motor per driven axle). The mechanical output of the APU, if indeed it is a rotating machine and not a fuel cell or thermophotovoltaic burner, is converted to electricity and then back to mechanical energy, which may then pass through a reduction gear and differential. The output of the APU need pass through the LLD only to the extent that the control strategy requires it in order to maintain a target state of charge (SOC) and an optimal load range for the APU itself.

Series HEVs also have significant efficiency, emissions, and powerplant size and mass advantages over conventional vehicles, even if the APU is an internal combustion engine (ICE). The advantages stem from the decoupling of the APU from peak power requirements and vehicle speed. Decoupling the APU from peak power requirements, through the use of an LLD, minimizes the load range or engine map. APU peak-power requirements for a series HEV are determined more by gradability than by acceleration, which is typically 1.6–1.8 times the requirement for gradability. Lower peak power requirements relative to average loads allow both a smaller engine (for added design flexibility and reduced mass), and an opportunity to run the engine closer to wide-open throttle, which reduces pumping losses. Minimum load can be a preset level based on the APU's range of lowest BSFC, rather than zero. Because the APU is decoupled from vehicle speed, the optimal combination of engine speed and torque can be used to provide the needed power output while minimizing emissions and fuel consumption.

A series hybrid drive allows a smaller APU to be used, in part because the engine map is decoupled not just from tractive loads but also from the vehicle wheel speed. This stems from the ability to extract maximum power for hill climbing and acceleration from the APU at any wheel speed, rather than only at the vehicle speeds which happen to correspond to peaks in the engine's output.

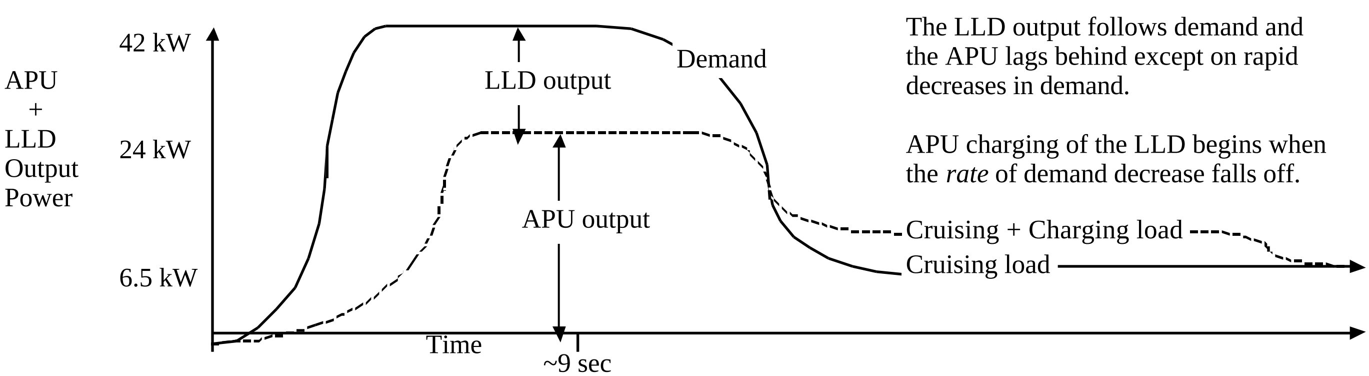
Series Hybrid Design and Control Strategies

Optimization of power storage devices for series hybrid drivesystems should emphasize specific power and efficiency, while maintaining enough energy storage capacity to provide multiple consecutive accelerations without excessive mass or severe voltage swings. This implies a balance point somewhere between the control strategy extremes of the range-extender and power-assist.

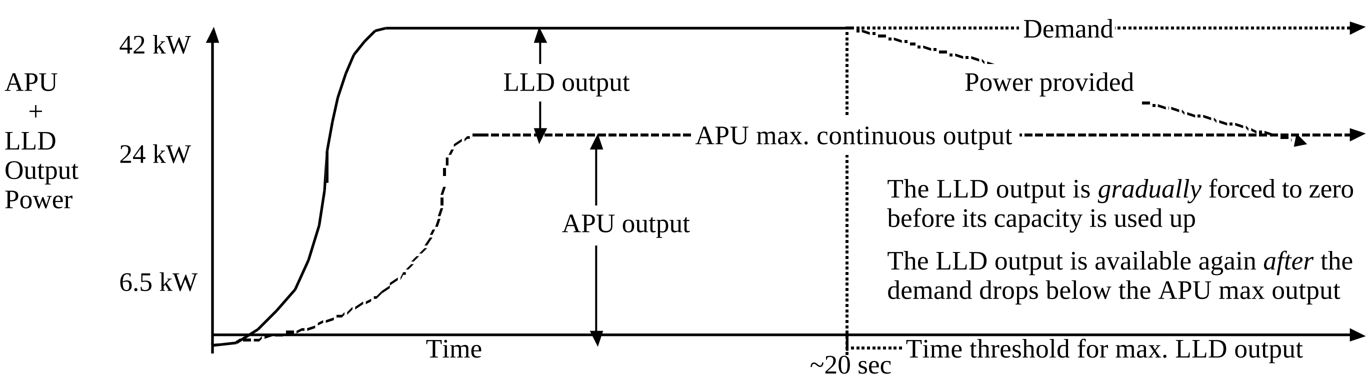
If the APU is an internal combustion engine, then an LLD which can handle numerous high-power cycles without degrading its life unduly is desirable for emissions reduction. If the LLD can handle all of the fast acceleration and regenerative braking transients, then a control strategy may be employed which allows the APU to follow only transients which are slow enough for oxygen sensor feedback control of the air/fuel mixture (Anderson & Pettit, 1995).

- To the extent that its range of low BSFC is sufficiently broad, the APU should follow the load, but with intentionally sluggish behavior during fast transients for *acceleration* and insufficient maximum power to meet the peak demands without the LLD. This will avoid some of the poor efficiency and emissions performance that the APU could have during fast transients.
- For the PNGV design scenario modeled, the STM Stirling APU should operate between 4.5 and 24 kW, with only maximum operating temperature to limit how long it is allowed to deliver the 24 kW maximum, and should turn off *as little as possible*. In other words, the APU should power hotel loads and charge the ultracapacitor or flywheel LLD if it is below 85% SOC (~70% for most types of batteries) when the APU would otherwise be 'idling,' thus avoiding the emissions and wear that could result from on/off operation.
- The LLD should cover all fast transients for acceleration and regenerative braking.
- The *target* SOC should be between 50%, to maintain minimum voltage if an ultracapacitor is used, and 85% to maintain available capacity to accept regenerative braking. The APU must turn on at no less than 50% SOC, and there must be a means of detecting rapidly dropping SOC during hard acceleration to be sure the APU is on *before* minimum voltage (50% SOC) is reached.
- Regenerative braking should be allowed to charge the LLD to 100% SOC, but the APU would be turned off at 85% SOC, unless there were sufficient road load and accessory load to use the minimum APU output—in this case, 4.5 kW.
- If a battery were used, rather than an ultracapacitor, the range of target SOC would be lowered to avoid using the 90–100% SOC range during regenerative braking (control strategy would vary depending on the internal resistance characteristics of the battery). A flywheel LLD would allow a larger range of SOC, with only the bottom few percent avoided by the control strategy to maintain high round-trip LLD efficiency.
- The LLD output needs to be gradually limited as it approaches the minimum SOC to avoid abrupt changes in vehicle performance.

The load-following behavior of the APU and LLD during fast transients for hard acceleration to highway speed on level ground and on a steep grade is illustrated below:



Maximum acceleration, followed by cruising at highway speed and LLD charging.



Maximum acceleration followed by maintaining maximum speed (*e.g.*, 65 mph @ EPA test mass) on a steep grade (*e.g.*, 6%), with *gradually* diminished peak power from the LLD to maintain sufficient SOC and traction-motor thermal headroom for subsequent accelerations. The 472.5 Wh (50 kW for 34 s) usable LLD capacity modeled for the PNGV scenario is sufficient for 1.84 full 0–60 mph accelerations at *gross* weight on a 6% grade, *without* any assistance from the APU or recharging from regenerative braking.

TRACTION MOTORS

The primary determinant of continuous motor power requirements is gradability, since this is the highest load which the drivesystem will have to overcome for more than the 9–25 seconds of maximum acceleration for various grade and payload combinations. Given the previously discussed design criteria, the continuous power required for gradability is 55–60% of that required for acceleration. Peak continuous power for traction motors at maximum bus voltage is typically about 30% higher than *rated* power, because rated power is measured at the nominal voltage of a battery under load. Thus, rated power should be used for motor selection. Maximum power requirements for scenarios discussed in this paper are based on spreadsheet modeling, and are in close agreement with the 50 kW/ton peak and 30 kW/ton continuous requirements for meeting PNGV criteria which have been established by the Office of Technology Assessment (OTA, 1995).

The three principal types of traction motors under consideration for BEVs and HEVs are asynchronous induction motors (IM), synchronous permanent-magnet (PM) motors, and synchronous switched-reluctance (SR) motors. Each has advantages, ranging from established manufacturing infrastructure and knowledge base to higher specific power or efficiency. PM motors generally have the highest *peak* efficiencies, but often over a narrower range of speed and load, depending on the specific designs being compared. While some IMs have essentially the same average efficiencies as PM motors (Cole, 1993a), the PM and SR designs are generally more efficient and have better specific power (Horvath, 1994; West, 1994). Strictly in terms of performance, current technology for traction motors is very competitive, with at least as much variation between specific designs of each type as between types.

Of traction motors tested at the Idaho National Engineering Laboratory, specific power was 0.67 kW/kg and 0.72 kW/kg for the best IM and PM motors, respectively (Cole, 1993a). Current IMs appear to provide the best performance per dollar for the near term, but PM motors with better specific power and slightly higher efficiency may overtake them as the price of magnet material is reduced (see below) and manufacturing investment is increased. The case for SR motors is similar to that of PM motors, with the addition of potential cost and application advantages (see below), except that the current level of R&D and manufacturing investment is much lower still (West, 1994; Hendershot, 1991). Much of the discussion which follows will focus on PM and SR designs, since meeting PNGV goals may depend on the high specific power they provide, and these technologies are less well known than IMs.

Both PM and SR types are electronically commutated brushless motors with windings only on the stator. However, a permanent-magnet motor has powerful (also high priced and heat-sensitive) magnets attached to its rotor. In contrast, the rotor in an SR motor is made exclusively of silicon steel laminates, with no magnets, and with no bars or windings such as occur on IM rotors. PM motors are currently more highly evolved for superefficient vehicular applications and are the choice of most U.S. designers, although some designers achieve high levels of control response and efficiency with advanced IMs.

Switched-reluctance[10] motors (Lovins & Howe, 1992) have been overlooked by many designers, particularly in the U.S., because of their past reputation for noise and excessive torque ripple, both of which have been overcome by careful design of the stator, rotor, power electronics, and control software. If designed to optimize efficiency and specific power, which they generally haven't yet been, the inherent physics of modern switched-reluctance motors enables them to outperform all other motor types (Blake and Lawrenson, 1992), including permanent-magnet motors, in efficiency, power per mass and size, overload capability, ruggedness, controllability, form-factor flexibility, simplicity, and cost (Hendershot, 1991).

Modern SR motors can deliver up to six times their rated continuous power for very short periods with system efficiencies well over 90% (SRD, Leeds, UK). Because SR motors can be designed to operate in very low speed ranges without much loss of efficiency, the reduction gear required for PM and IM types could possibly be eliminated, improving mechanical efficiency significantly. While the overload capacity is an important indicator of robust design, the potentially high peak power, relative to continuous rated output, is unfortunately of little use (except as a safety margin) in automotive traction motors, since the motor must be sized for gradability.

At a given torque rating and production volume, a well-designed SR motor for industrial applications, including its electronic controller, costs less to manufacture than a single-speed IM with no controller. This is because the SR motor will be one or more frame sizes smaller for the same torque, need simpler coil-winding, and have a far simpler rotor. Similar comparisons with the cost of manufacturing PM motors also favor SR designs because they have no magnets and require smaller power switches. PM motors would rely on neodymium-iron-boron (NdFeB) or other rare-earth magnets; SR motors have no magnets. SR motors would also require less labor for rotor manufacture and assembly and for coil winding (Hendershot, 1991), and unlike PM motors, need not be assembled (or disassembled for repair) in a cleanroom to prevent ferrous dust and scrap from adhering to the magnets.

PM motors with much higher performance than the old Alnico and ferrite versions have been kept rather expensive by modest production volumes and by the monopoly U.S. supermagnet producer's practice of pricing its rare-earth-iron-boron compound at opportunity cost, just below its costly but magnetically inferior samarium-cobalt competitor. But partly through Russian and Chinese competition, the price of rare-earth magnets has recently fallen 50% and is expected to drop another 50% by 1999 (West, 1994).

SR motors also have important mechanical and design advantages. Their ability to function effectively and with exceptional torque at very low shaft speeds can eliminate the need for reduction gears between the motor and wheels. In practice, it may still prove desirable to use a smaller, faster motor

[10] This name, though technically correct and accepted, can be confusing to non-specialists. "Reluctance" is the tendency of iron to align itself with an applied magnetic field; this principle is what makes the motor work. But what is switched is not the reluctance, which is a constant property of the iron rotor, but rather the magnetic field, which is rapidly switched by digitally controlled power electronics between a series of surrounding pole pairs in the stator to create a rotating magnetic field. The rotor then follows the rotating field.

together with a single, lightweight gear, or perhaps even to integrate two pancake-shaped motors into a planetary-gear design so as to obtain a very wide speed and torque range with less weight and cost. Such conclusions depend on SR design exercises not yet completed.

The lack of all but tiny hysteresis and eddy-current losses in the rotor—iron losses only, since the rotor contains no copper—also means that excess heat needn't be extracted from the spinning rotor, which is surrounded by the stator and casing. Rather, the motor's heat arises almost entirely in the stator, which has a higher thermal mass and is encased in the heat-dissipating shell. And with its unique operational flexibility, at least equal to that of a doubly excited DC motor, the switched-reluctance motor independently controls speed and torque in real time, over a wide range, in all four quadrants (forward and reverse, motoring and braking). This permits an unprecedented range of performance, separately optimized for accelerating and electronic braking, and continuously readjusted for maximum efficiency under all instantaneous conditions.

Both PM and SR motor types use iron and silicon for the high-grade, grain-oriented, silicon-steel rotor and stator that conduct the magnetic fields. Amorphous (glassy, noncrystalline) magnet iron containing silicon and boron, developed by Allied Signal, cuts hysteresis losses by an order of magnitude, but is brittle and hard to fabricate. The recent development by Electro Research International in Parkside, South Australia, of a process for forming and cutting amorphous magnetic materials may allow the use of smaller, lighter stator cores. This new cutting technology is being licensed to German and U.S. firms. Unique Mobility (Golden, CO) has developed cores pressed from plastic-coated powder, and if adapted to amorphous powder this technology could evade the brittleness and uneven thickness of amorphous iron. These developments promise even smaller and lighter motors of all kinds.

Optimally, four motors might be used (one for each wheel) to eliminate the need for differentials, axles or driveshafts, and possibly even axle joints, all of which add weight and complexity and reduce efficiency. Additionally, four motors, each under digital control driven by real-time shaft-angle sensors, could provide all-wheel anti-lock regenerative braking and traction control, both with a speed and responsiveness superior to any system available today. The downside of this arrangement is that smaller motors are generally less efficient, except at very high speeds, and have a lower specific power (power-to-mass ratio). The gains from reduced mechanical complexity and driveline component mass must then be weighed against the trade-offs of multiple smaller motors. If such an arrangement were used, motors could be either built into the wheel hub-carriers or located inboard using ultralight tubular composite axles with conventional, but smaller (in proportion to *gross* vehicle mass reduction), constant-velocity axle joints. Whether to integrate motors with the hub-carriers or put them inboard is a question of seals and heat extraction (which depends on motor design, cooling method, and efficiency) and of unsprung weight and suspension design as discussed under Mass Distribution and Vehicle Dynamics.

Motor Controllers and Inverters

The complexity of electronic engine management controls in current cars, which operate over a wide range of speed and torque while attempting to save fuel and minimize emissions, might be reversed by HEVs' minimized engine speed and load operating ranges. At the same time, though, substantial control and power electronics will be added for integration of the APU, LLD, and traction motor(s).

The efficiency of power electronics is generally improved by constraining the bus voltage to a relatively narrow range (Anderson & Pettit, 1995). The ability to handle extreme voltage fluctuations also drives up the cost of controllers, as parallel sets of components have to be introduced to handle the very high currents. The cost of power electronics, which is currently seen as one of the primary obstacles to mass production of HEVs (L. Oswald, GM, personal communication, April, 1995), is expected to be roughly halved within the next ten years (West, 1994).

Power electronics are rapidly becoming quite small and lightweight. Five years ago, a 2.5-MVA advanced power switch developed by Nishizawa-sensei at the University of Sendai—perhaps 40 times the peak power rating of the entire propulsion system modeled for this paper—was about as big as a hockey puck. Today, a complete[11] packaged hybrid-power-chip controller for an electronically commutated three-phase motor rated at 2.5 peak or 1.5 continuous kVA, including all signal, control, diagnostic, and power electronics, weighs only ~60 g. The equivalent per-wheel controller for a hybrid would have about 13 times that continuous power rating and would weigh perhaps 6–8 times as much—about 0.5 kg—or perhaps less, because a single 24-kW power switch today can be only the size and about the weight of an aspirin tablet, and each motor would need only a few such switches per pole pair.

The Unique Mobility controller, currently in experimental BMW and Pinninfarina BEVs, is an automotive-scale example of the trend towards very lightweight power electronics. This controller can handle 120 kW peaks, is designed for continuous operation at 53 kW, and weighs just 11.4 kg[12], even though it is not yet thoroughly mass-optimized.

[11] Except for three resistors, one potentiometer, a trip switch and four capacitors (three very small and the other 480 µF) required for the application circuit, and some grams of potting and sealing polymers. The particular unit assumed here for illustration is the OMC506 30-A (continuous), 50-A (<1% duty cycle), 18–50 V, 92%-efficient closed-loop 3-phase DC brushless motor controller using 20-kHz pulse-width modulation and made by Omnirel (Leominster, MA). Its MP3T package including an aluminum heat-sink baseplate (designed for thermal contact with a larger dissipator) is 51 x 102 x 12 mm, excluding the 34 protruding electrical leads.

[12] Not including coolant, cooling system, or any sort of battery charging or thermal management devices.

LOAD LEVELING DEVICES

If conventional batteries optimized for BEV applications are used for the LLD in a hybrid, the excessive addition of mass can impair the design of the whole vehicle. Because of mass compounding, a heavy battery pack adds considerable mass to the vehicle structure, as well as drivesystem, chassis, and braking components required to accelerate, carry and stop the added mass. Aside from mass optimization, LLD selection for an HEV is driven primarily by the drivesystem control strategy and high specific power requirement.

A BEV must maximize specific energy for driving range with reasonably fast charging and long battery life at an acceptable cost. The energy recovered from braking and fed back into the batteries is quite minor compared to the large amount of energy stored for range. In contrast, HEVs have much less need for storing *energy* per unit mass, because their long-range driving energy comes not from batteries but from chemical fuel, which has 50–100 times the specific energy of current battery technologies. A range-extender hybrid strategy would depend more on the energy storage of a BEV with modest range, but still require relatively high specific power if the LLD mass is to be significantly less than the storage device in a BEV. HEVs which tend towards a power-assist strategy require high specific *power* and high *cycle efficiency* so that the APU is buffered from the transient loads which occur during acceleration and braking. The internal resistance must be low to allow efficient high-rate charging and discharging from regenerative braking and acceleration.

The combination of potentially limited APU transient capability (depending primarily on how the APU emissions are affected by transients) and internal resistance of the LLD requires careful control strategy, and ultimately affects the efficiency of regenerative braking. Unless the LLD capacity is very large, as in a range-extender HEV, the ability of the APU to decrease its output rapidly is of significant concern. If, for example, a period of high-power acceleration is immediately followed by hard braking, but the APU cannot drop its output sufficiently before braking begins, excess power coming from regenerative braking may have to be dumped. The internal resistance of the LLD then becomes an important control strategy determinant. A device capable of handling extremely high power, such as a flywheel or ultracapacitor, may be able to soak up the simultaneous output from the APU and regenerative braking. With a lower-power LLD, however, the voltage could rise dramatically, possibly leading to an overvoltage condition. This would unload the APU, and, in an extreme case, cause an overspeed that might damage the APU (Anderson & Pettit, 1995).

Because HEVs allow control strategies for which the energy storage device needs high peak power but very little energy capacity, there is also the potential for much lower cost relative to that of a BEV. This appears likely for high-power batteries, if they can be developed as predicted, and even more so for ultracapacitors. Flywheels, at a relatively high initial cost, may be the first technology with sufficiently low mass, high power, and frequent-cycle tolerance ready for HEVs.

The lower energy-storage mass in an HEV decompounds some of the performance and cost relationships that snowball in a BEV with a heavy battery pack. The peak power requirements for all of the drivesystem components, and thus their cost as well, are reduced by trading the heavy energy storage device required for long range in a BEV for a manyfold lighter LLD, fuel tank, and APU. The relative importance placed on regenerative braking efficiency at gross weight might, however, be a limiting factor in terms of component cost. While peak power for acceleration can be fixed at a level which provides very good acceleration at M_{EPA} and simply acceptable acceleration at gross mass, efficient regenerative braking may require much higher-power operation of the LLD at gross mass than at M_{EPA}. For a given payload capacity, the reduced driveline mass of an HEV could allow more efficient regenerative braking and better acceleration, reduced component cost, or some balance of both.

The performance of the LLD needs to meet design criteria at the lowest design SOC and then tail off gradually for safety reasons. These characteristics must be maintained despite normal degradation of components over the design life, even at very low or very high ambient temperatures. Temperature sensitivity is only of significant concern for electrochemical LLDs, which can be addressed for most climates with insulation and careful HVAC-load and battery-thermal management, as demonstrated by the Vermont Electric Vehicle Project.

Ultracapacitors and flywheels currently appear better suited than electrochemical batteries to the high-power, frequent-cycle requirements of HEVs (Automotive Engineering, 1992; Burke, 1994; Post, 1993). Some of the electrochemical battery technologies below, however, may yet prove to be as well suited. Flywheels and ultracapacitors don't have outstanding energy density, but this is of increasingly less importance as the control strategy approaches the power-assist end of the spectrum. They do not, however, have many of the drawbacks of current battery technologies such as life-cycle limitations under deep-discharge or frequent micro-cycling conditions.

Advanced Batteries

Battery efficiency is directly related to internal resistance, which tends to rise rapidly in the top 10% of state of charge (SOC) during charging, and in the bottom 20% of SOC during discharge. In order to minimize resistive losses, the control strategy for batteries in a series hybrid must maintain the SOC around 50–70%. This allows enough headroom to absorb high-power short-duration regenerative braking events typical in urban driving, while maintaining enough capacity for longer acceleration events. (Anderson & Pettit, 1995)

The degree to which the lower end of the battery capacity is depended upon for long hill-climbing events will affect available power for subsequent accelerations, and may require extremely robust power electronics to handle the low-voltage high-current swings. Battery life will also be decreased by the depth and frequency of discharges. These trade-offs need to be weighed against the increase in APU power capacity, and thus engine map and emissions controls complexity, which would be necessary to avoid them.

Rapidly moving energy in and out of a battery heats its surfaces, accelerates its aging, and may substantially reduce its cycle efficiencies. If a battery is to be used, nickel-cadmium (NiCd), nickel-metal-hydride (NiMH), or other types with good long-term tolerance of ‘micro cycling’ are preferable. The use of conventional lead-acid (PbA) or similar battery types for the LLD tends to push the control strategy towards a range extender to reduce micro-cycling. On the other hand, a power-assist control strategy could also prolong battery life if the APU were allowed to follow the load enough to prevent deep discharges under all but the most severe conditions. Even PbA batteries, for example, are degraded less *per kWh throughput* if cycled more shallowly (Anderson & Pettit, 1995). And this would probably be the case, as the sizing of the LLD is determined primarily by high peak power and energy for multiple accelerations without regenerative braking between them, which would occur very seldom for most drivers. Because discharges tend to be shallow rather than deep for power-assist HEV control strategies, it seems plausible that, despite frequent cycling and high *rates* of throughput, battery life and efficiency might be degraded far less. There has not yet been sufficient research, however, to confirm this logical conclusion.

Ovonic Battery Company (Troy, MI) estimates that NiMH batteries optimized for specific power could provide 800–1000 W/kg at a specific energy of ~50 Wh/kg (Fetcenko & Dhar, OBC, personal communication, August 1994). In their commercially available form, these batteries are conservatively rated by Delco Propulsion System (Anderson, IN) at 220 W/kg and 70 Wh/kg. The anticipated trade-off of specific energy for specific power results primarily from increasing the surface area of the electrodes to reduce internal resistance.

Specific power of more than 800 W/kg from 0–70% DOD has been achieved in experimental bipolar PbA batteries, using the USABC peak power test procedure, at Bolder Technologies (Wheat Ridge, CO). In 1994 tests, these 1.5-Ah cells managed 15,000 "shallow discharges," but only 300 deep discharges. Charge acceptance, on the other hand, has been shown to be very high, with a 2-V nominal 1.2-Ah cell recharging to 80% SOC in 3 minutes and 100% SOC in 7 minutes, using a 2.65-V constant current charging regime. Tests of a pack of 2-V cells as an LLD on an urban driving cycle demonstrated discharge rates up to 30 C[13] and charge rates for regenerative braking up to 10 C, with voltage fluctuations of less than +22% and –13% (Rudderman, *et al.*, 1994). It appears, based on the documentation, that the maximum rates of charge and discharge were limited by the prescribed demand rather than the internal resistance of the cells. Further development and testing demonstrated 40,000 10-second cycles at an 8 C rate (10 A), but fluctuating within just 6% of the initial 50% SOC of a relatively large pack (B. Nelson, Bolder Tech., personal communication, July 1995).

Small lithium-polymer laboratory test cells now being developed for commercial applications at Poly Plus Battery Company (Berkeley, CA) have demonstrated 250 Wh/kg and peak power of 1–2 kW/kg for short durations on the order of 10 seconds. Further development could potentially extend that to around 30 seconds, which would be sufficient to provide for maximum acceleration of a fully loaded vehicle meeting PNGV criteria. The principal challenge these and other advanced batteries face is upscaling for automotive application. Thin-film (~4 micron) lithium-ion cells now under development at Tufts University may be capable of providing peak power up to 8 kW/kg at 500 Wh/kg if preliminary findings are correct. Such batteries could be recharged very rapidly, like ultracapacitors and flywheels, and may have the added advantage providing high specific energy at a very low cost. This would open opportunities for parallel-hybrid configurations and range-extender control strategies, and possibly even BEVs capable of competitive performance and cost.

Research to date has focused more on specific energy than specific power, leaving much opportunity to develop frequent-cycle tolerant, ~800-W/kg, 35–50-Wh/kg electrochemical batteries—very probably even within the PNGV time frame.

[13] 30 C is 30 times the rate required to discharge a cell fully in one hour.

Ultracapacitors

Ultracapacitors, rather like very-high-power, low-capacity batteries, provide the fast charge and discharge capabilities (high specific power) required for HEVs. This is particularly important for the recovery of braking energy, which tends to come in large, fast doses as the vehicle approaches a stop or abrupt change in traffic flow, especially when at high speed. Since they store electrons physically rather than by reversible chemical reactions, ultracapacitors also exhibit excellent cycling durability. They should last as long as the car, even when rapidly and frequently deep-discharged. Their round-trip cycle efficiency range is around 92–98%, depending on rate of charge/discharge, compared to conventional PbA at ~70% and NiMH at ~80% for low power flows, and considerably worse under high-power operating conditions. Ultracapacitors are slightly sensitive to low temperatures, but much less so than even the least cold-sensitive batteries, hence even easier to fix with insulation and thermal management. The principal limitation of ultracapacitors is their low specific energy, which is currently around 6–7 Wh/kg (Burke, 1995a).

Because the voltage of an ultracapacitor varies directly with SOC, much of its capacity is likely to be unusable. For example, if the minimum controller voltage is 50% of the maximum, then only 75% of the stored energy can be removed from the ultracapacitor before its voltage is halved. Ultracapacitors are thus likely to be suitable only for light vehicle applications with low specific energy requirements.

Ultracapacitors under development at Maxwell Laboratories have demonstrated outstanding specific power of more than 2–4 kW/kg, compared to roughly 150–350 W/kg for currently available batteries and 400–800 W/kg for cells that could be or are being optimized for HEVs (see above). Constant power discharges have been done at up to 4 kW/kg, with a round-trip efficiency of 93% at 1.5 kW/kg (Burke, 1995b). There is, however, still fundamental work to be done in materials science, such as the microscopic morphology of electrode materials and formulation of electrolytes, to meet the established specific-energy goal of 10–20 Wh/kg. Further understanding of these elements must then be followed by the development of new manufacturing processes to achieve the desired material properties and relationships (Borroni-Bird & Osteryoung, 1995). If these basic research efforts meet with reasonably expected success, and prices for electrolytic-grade carbon come down somewhat to about $5–6/lb, a 600-Wh ultracapacitor LLD, depending on specific energy, may cost only $200–400 around the year 2000 (Burke, 1994a).

Flywheels

Electromechanical flywheels used to be heavy, low-performance, and potentially dangerous because they contained high-strength metal wheels spinning relatively slowly but liable to create shrapnel if they failed. But the same advances that allow commodity aerospace-grade carbon fiber to achieve ultimate yield strength around 0.7 million pounds per square inch (4.8 GPa), and even higher with costly experimental carbon, now permit extremely light but fast rotors with containable failure modes, very small precessional moments, and relatively modest system costs. Combined with new advances in supermagnets, magnetic and gas bearings, stability and control theory, software, microelectronics, and power electronics, these remarkable rotors, with supersonic rim speeds (up to several thousand miles an hour), now make possible flywheels appropriate for automotive applications.

Flywheels with a specific energy of 50–100 Wh/kg, similar to good electrochemical batteries, and specific *power* up to at least several *kilowatts* per system kg—about 10–100 times that of an electrochemical battery—are likely to be the first high-power LLDs suitible for production HEVs (L. Oswald, GM, personal communication, April, 1995). The first units available will probably have a capacity of about 40 kWh/kg. The primary limiting factor for flywheels is cost, which might initially constrain their use to a single unit of about 1–1.5-kWh capacity per vehicle. Thus, like ultracapacitors, flywheels will probably be appropriate for applications such as light HEVs that require relatively little energy storage capacity, but would do little to reduce mass or cost for BEVs.

The very high specific power depends almost completely on the wire type and diameter in the windings and the power ratings of the switching semiconductors. Specific power of 5 kW/kg has been successfully demonstrated from a 1-kWh, 20-kg laboratory prototype (flywheel, drive, and vacuum housing only) (Post, 1993), and higher power ratings appear feasible with present technology. Since most series hybrid passenger vehicles could need only 0.4–0.6 kWh of electric LLD capacity (Burke, 1991 and 1994a), and 1.2-kWh flywheels already exist that store 30 Wh per *system* kg (including the controller at ~10 kg) (L. Oswald, GM, personal communication, April 1995), a sufficient flywheel system (600 Wh) with controller could weigh just 20 kg (R. Post, LLNL, personal communication, January 1995). To avoid speculation about scaling, a more conservative projection might stick with the 1.2 kWh capacity now being developed, and still the total weight with controller would be just 40 kg.

Flywheels with filament-wound, carbon-fiber rotors spinning in a hard vacuum on magnetic bearings operate at speeds around 100,000–200,000 rpm. There is virtually no mechanical contact between the rotor and other structures; advances in bearing technology now permit at least the weight of the rotor, and most of its sideways forces, to be supported by magnetic fields alone, and those fields can be provided almost entirely by permanent magnets, only slightly supplemented by active electromagnetic control signals (R. Post, personal communications, 1993–1995). Because of the mathematics of whirl instability, exact balancing of the rotor is also not critical.

The flywheel design developed at Lawrence Livermore National Laboratory (LLNL) uses a non-magnetic "thimble" in the stainless-steel vacuum vessel, which comes up inside the bottom of the rotor shaft. The rotor contains a Halbach array of neodymium-iron-boron magnets that creates an almost perfectly linear magnetic field. This passes through the thimble to interact with special wire windings fixed in position inside the thimble. The windings are connected to power electronics and microelectronics to form a permanent-magnet motor.

Because the rotor encounters virtually no friction from its magnetic bearings and from the few remaining molecules of air in its vacuum housing, it loses well under 1% of its energy per day (better than most batteries). The rotor hub can be interference-fitted into the rotor after being cooled with liquid nitrogen, so the rotor materials are preloaded with a compressive force that partly offsets the tensile stress of rotation (R. Flanagan, personal communication, July 1994). The lack of mechanical friction, electrochemical processes, and iron losses together raises in-out cycle efficiency to 96–98% (R. Post, personal communications, 1992–94); the lower end of this range has already been demonstrated and the upper end, limited mainly by copper I^2R losses and by inherent physical processes in semiconductors, appears achievable.

Flywheels are now the subject of intensive R&D by numerous firms, chiefly in the United States. Some of those firms expect to bring stationary-source versions to market by 1996 for uninterruptible power supplies, utility powerline conditioners, and other short-term, high-power, localized, stationary applications. Leading developers such as LLNL consider the shock-mounting, gimballing, and failure-containment requirements for vehicular use (even considering potholes) manageable enough that their products could be engineered for vehicular use by late 1996 or 1997. Precessional forces on the rotor bearings are best dealt with by minimizing rotor diameter (since its precessional moment, like the energy to be dealt with if the rotor flies apart, increases as the fourth power of radius) and by providing ceramic backup mechanical bearings for occasional momentary touchdown in case of severe shocks. Rotor failure modes need careful analysis, but can be dealt with using lightweight structures analogous to those used in aircraft fanjets. Containment becomes fairly straightforward if the carbon-fiber rotor can be designed to disintegrate consistently in the typical failure mode, producing no shrapnel but rather a soft, hot, whirling cloud of fibers and dust that is erosive but not ballistically penetrating.

AUXILIARY POWER UNITS

Several promising technologies being developed may be appropriate for hybrid vehicles, depending on series or parallel configuration and on the relative importance of efficiency, emissions, size, weight, and cost. These include internal combustion (IC) piston-engine, turbine, and Stirling-cycle generator sets, thermophotovoltaic burners, and fuel cells.

Like the traction motor(s), the APU should be sized for gradability, if the LLD is to be optimized for high specific power rather than energy storage capacity. With the road load and design assumptions previously discussed, the APU would have to supply about 24 kW of electrical output, or a bit less than 30 kW/ton at the wheels. If the LLD were a battery with lower specific power, which might require the vehicle to carry several times the storage capacity and mass of other options, the APU might be sized closer to the theoretical average load, with some margin for variations in driving conditions.

Unless the road loads resulting from the vehicle design are reduced substantially further than is assumed in this paper, *average* APU efficiency, including the alternator if the APU output is mechanical, must be at least 30%. This would be equivalent to an IC engine at 33% efficiency with an alternator at 92% efficiency. Furthermore, this level of efficiency must extend over a relatively wide range of engine speeds (if output is mechanical) and loads.

Low BSFC over a range of speeds for a relatively low-speed mechanical APU, even in a series hybrid configuration with the APU decoupled from vehicle speed, is necessary to allow some operation at low speeds, which are more easily tolerated by the APU, and at higher speeds, which are more easily tolerated by an alternator (Anderson & Pettit, 1995). Low BSFC over a range of loads is advantageous because it accommodates a larger control strategy turndown ratio (ratio of maximum to minimum APU output). This minimizes on/off cycling of the APU, which might otherwise produce unacceptable emissions and degrade the life of the engine. Low mechanical inertia is also desirable, particularly if the LLD capacity is relatively small or if the internal resistance of the LLD is relatively high. As discussed in regard to the LLD, this may be necessary to maintain efficient regenerative braking and to protect the APU from the potentially damaging effects of overspeed operation (*ibid*.).

While modern spark-ignition engines have relatively high levels of peak efficiency, they do not yet appear to be capable of maintaining the levels of efficiency necessary for achieving PNGV goals. Stirling engines and fuel cells have the advantage of consistent emissions even during relatively fast transients. These APU options also have slower reaction to transients, and thus require an LLD with low internal resistance if regenerative braking efficiency is to be maximized (see LLD section). Thermophotovoltaic burners and fuel cells have the advantage of being solid-state, so they aren't subject to damage from overspeed conditions or other mechanical wear and tear. With no moving parts other than auxiliaries such as a coolant pump or intake compressor, they may also be cheaper to manufacture at high volumes.

Liquid fuel storage could be in lightweight, inexpensive, roto-molded polypropylene tanks. Gaseous fuel could be stored in high-pressure, filament-wound carbon fiber tanks with thermoplastic or metallized-polymer film liners. These tanks may become lighter as the U.S. Department of Transportation gains enough experience with and confidence in such tanks to relax its requirement for extremely large safety margins, which inflate both mass and cost for high-pressure tanks.

Internal Combustion Engines

Combustion-driven generator sets could include direct-injection diesel engines and a variety of high-performance rotary or two- and four-stroke engines, given sufficient efficiency gains in the spark-ignition engines. With reduced tractive power requirements for a load-leveled APU in an efficient vehicle design, the APU need not go the lengths conventional engines do to pack high torque into a small volume. If designed instead more like aircraft engines, they would place less stringent demands on materials and could therefore make parts lighter and more durable: the engine would become larger per kW, but also lighter, longer-lived, more reliable, and probably somewhat cheaper.

Orbital (Perth, Western Australia) has developed a wide range of automotive, marine, scooter, and other two-stroke engines. Orbital claims that a typical automotive engine would weigh 40% less, be 40% smaller, have approximately 200 fewer parts, cost 20% less, use 12% less fuel, and meet California ULEV emission standards at 70–80% lower marginal cost than good four-stroke engines with comparable power output (Steve Hill, Orbital, personal communication, December 1994). Orbital engines have been used in numerous prototype vehicles by Ford, GM, and European automakers, and have successfully passed ULEV testing by the California Air Resources Board.

Newbold & Associates (Allenspark, CO) has developed a multi-fuel turbo rotary engine, very unlike previous rotary engine designs. Originally developed for aircraft, and therefore mass-optimized, it has a rotating block with pistons that do not actually recipricate except relative to the block which rotates around an offset centerpoint. Newbold claims an output of 3.3 kW/kg or 2 hp/lb (about three times the specific power of GM's Orbital-derivative engine for the Ultralite), 25% better fuel efficiency than a typical four-stroke, low emissions, considerable parts reduction, low maintenance, and extended life expectancy. Newbold & Associates has formed a joint venture with TAM Motors to begin production of turbo rotary engines for light aircraft, and expects to license the technology to other manufacturers in the near future (Martin, 1994).

Split-Cycle Technology, Ltd. (Arundel, Australia) has developed a radial two-stroke multi-fuel engine that burns fuel more slowly and completely (thus with higher efficiency and ultra-low emissions without add-on emission controls), has up to 600 fewer parts and no crankshaft, and is less than 10% of the size and weight of a comparable four-stroke (Luck, 1994).

Because ceramics processing technologies have advanced so much in the past five years, complex ceramic parts for high-temperature engine applications, including delicate finned rotors for turbochargers at one-third the weight of their super-alloy counterparts, are now being profitably produced from silicon nitride powder for niche markets. Technical cost models developed by the Massachusetts Institute of Technology (Mangin *et al.*, 1993) indicate that large-scale commercial manufacturing of ceramic engine parts will be possible in the near future. Cost reductions for low-pressure injection molding of ceramics have been primarily responsible for this shift from what was not seen as a competitive technology until recently. Although the cost of simply *substituting* ceramic parts into an *existing* engine design typically isn't justified by the marginal gain in performance, such advantages as reduced weight, noise, and wear and improved engine power, which accrue from the integration of ceramics at the *design* phase, could be impetus enough for the mass-production of automotive engine ceramics (*ibid)*.

DuPont's Zytel fiberglass/nylon 6,6 composite and GE's blow-moldable Noryl GTX are but two of a plethora of recently developed polymer automotive engine products that typically weigh 60% less and cost 75% less than the parts they replace (Demmler, 1994). Carbon-carbon composites, aluminum and titanium metal-matrix composites, and a long list of new light alloys originally developed for the National Aerospace Plane (NASP) are being optimized for automobile engines by Texas Instruments' Metallurgical Materials Division. They hold promise of improving high-temperature tolerance, lowering friction and wear, and reducing engine weight by 50%, including rotating and reciprocating masses, which would all improve efficiency. The high temperature resistance of some of these materials could even allow the weight of exhaust manifolds and catalytic converters to be cut in half (Ashley, 1994). A low-cost, high-quality pressure infiltration casting process for metal-matrix composites, developed at the Massachusetts Institute of Technology, is being commercialized by MIT spin-off MMCC, Inc. for automotive and other applications. MMCC claims that the pressure infiltration casting process will cost-effectively produce a long list of defect-free engine, brake, and suspension components with superior stiffness (hence ultralight weight) and thermal characteristics (MMCC, 1994).

Gas Turbines

Small gas turbines, typically with ceramic or superalloy rotors, have become highly developed for military applications such as tanks, aircraft auxiliary power units, and cruise missiles, where their cost has been readily justified. They have the potential for very high specific power (0.6 continuous–0.8 peak kW/kg for ~24–30 kW is typical) and power density because they can run at speeds around 100,000+ rpm. Efficiency is typically about 30–40%, depending on design and the incorporation of a recuperator. They can also use direct drive PM or SR generators, which are compatible with such speeds because of the high bursting strength of their very simple and robust rotors, and thus can have *very* few moving parts. Multi-fuel capability and very smooth operation are also readily attainable.

The principal constraints on the size of a gas turbine for automotive applications are the significant quantity of airflow required (λ = 4–5), aerodynamic efficiency of the turbine rotor, and necessity of a recuperator to preheat the intake air if high efficiency (34–40% peak) is to be maintained.

Some U.S. and foreign (chiefly British) firms and academic research groups believe that 20 kW could be extracted from a turbine/generator package about the size of a champagne bottle, at the expense of some efficiency. The loss of efficiency in downsizing would result from the limitations of turbine rotor tip clearance, boundary layer effects, and aerodynamic friction. A recuperator to preheat intake air for efficiency could also double or even triple the size of the overall package. Noise suppression systems (damping and possibly electronic anti-noise) would also add to the size of the total package. Even with all auxiliaries, however, this approach shows promise if indeed the new ceramics manufacturing techniques mentioned above prove to be cost effective. (C. Besant, personal communications, 1993–1994)

The development of low-cost gas turbine generators with efficiency around 30% and emissions well below ULEV standards by Allied Signal Aerospace (Allied Signal, undated), NoMac Energy Systems, Inc. (MacKay, 1993), and others may offer an appropriate compromise of size, cost, and efficiency for HEV applications.

Stirling Engines

Stirling cycle engines have the potential to provide efficiency similar to or better than the best diesel engines, but with lower cost, noise, vibration, emissions, and engine mass. With ceramic materials on the hot side of the engine, peak efficiency can be 50% or more (Musikant, 1985). The continuous external combustion of these engines is inherently quieter, cleaner, and easier to control than combustion in an internal combustion engine where the air-fuel mixture is compressed. With 3–4 fold smaller intake air-flow requirements (λ=1.2), Stirling engines can potentially be more compact than comparable gas turbines. Furthermore, elaborate recuperators (intake air pre-heaters) are not needed to get high efficiency.

Decades of research on Stirling cycle engines have, in most cases, failed to produce a Stirling engine with high efficiency in a package that is small, light, and inexpensive enough for automotive applications. However, a novel and elegant Stirling cycle engine currently under development at Stirling Thermal Motors (STM) (Ann Arbor, MI) for commercial hybrid-electric automotive applications appears to have overcome the obstacles that thwarted the success of previous designs (Bennethum, *et al*., 1991; STM, 1995). These engines are the culmination of more than 35 years of Stirling engine development at N.V. Philips and STM.

The STM engine's swashplate drive allows a continuously variable load range without complex, bulky, and inefficient systems to alter the working gas pressure. The design is mechanically very simple, which should facilitate cost-competitive manufacturing. A pressurized crankcase and inexpensive steel cylinder sleeves effectively contain the working gas so that performance and efficiency are not degraded over time. Piston seals are on the cold side to improve service life. Low emissions are maintained by keeping the flame temperature relatively low. (*ibid*.)

Peak efficiency of 40% can be achieved with an STM engine made from inexpensive aluminum and steel alloys (*i.e.*, without ceramics, expensive alloys, or other exotic materials). With nearly flat torque and efficiency curves, the efficiency falls to no less than three percentage points below peak over approximately 70% of the total load range. For a given swashplate angle, the ratio of power output to engine speed remains essentially fixed. These attributes contribute significantly to vehicle efficiency and make hybrid control strategies relatively straightforward. (STM, 1995)

Using standard materials, mass can be reduced by 47%, but at the expense of peak efficiency. (For example, an all-metal engine rated at 28 kW continuous brake output would weigh 76 kg at 40% efficiency and 40 kg at 34% efficiency.) Custom-made auxiliaries, lighter materials for engine parts, and limited use of ceramics could all allow mass reduction without loss of peak efficiency. Alternatively, ceramics could be used to boost efficiency nearer to 50% without added mass. Together, these measures could reduce mass *and* raise efficiency well above 40%. (STM, 1995; Musikant, 1985)

Thermophotovoltaics

Thermophotovoltaic (TPV) generators optically collect band-pass filtered infrared radiation from controlled fuel combustion in a ceramic emitter, then concentrate that infrared onto photovoltaic cells whose bandgap matches the peak infrared wavelength. This approach combines the consistently low emissions and fuel efficiency of continuous, low-pressure combustion with the solid-state conversion of heat *directly* into electricity (Seal and Fraas, 1994). With the efficiency of a gas turbine, ultra-clean and -quiet combustion, fuel flexibility, no moving parts, and very high reliability, TPV generators offer an attractive new set of capabilities, now being lab-tested, which will probably join the competition in the late 1990s. Since TPV generators use only fixed infrared photovoltaic cells and a stationery burner, their manufacture would be more closely related to the electronics and gas-appliance industries than to that of automobile engines. The gallium-antimonide cells are currently made only in very small quantities by JX Crystals (Seattle, WA) using crystals grown in China. However, the manufacturing of the cells is inherently quite inexpensive, since many tiny concentrator cells can be made on a single wafer, and high-quality three-inch-diameter single-crystal wafers are not difficult to produce using a zinc diffusion process for junction formation developed at Boeing (Fraas *et al*., 1993). The cast ceramic infrared emitter and novel "barnacle-top" burner run at 1700–2000 K, pushing the total generator efficiency above 30%.

Fuel Cells

Fuel cells are akin to electrochemical batteries, but use a continuous supply of chemicals (a fuel and an oxidant, such as hydrogen and oxygen) to drive a catalyzed electrochemical reaction. This flameless equivalent of combustion directly produces electricity with no byproducts other than air, water, and carbon dioxide. Early versions based on such chemistries as phosphoric acid and molten carbonate do work but are relatively bulky, heavy, and costly. The two chief prospects for dramatic reductions in size, mass, and cost are proton-exchange-membrane (PEM) cells (Williams, 1993) and monolithic high-temperature solid-oxide cells.

Conversion efficiency for good PEM cell stacks can average around 50% with peak efficiency of ~65%. PEM fuel cells also have the fundamental advantage of maximum efficiency at part load, which is well suited to the tractive loads of most driving given that the APU is sized for gradability, as discussed previously. Efficiency does fall off quite steeply at very low loads, but this small portion of the load range could be avoided with an appropriate control strategy. Even with the addition of an on-board reformer, Idaho National Engineering Laboratory has demonstrated 45% system efficiency and an average of roughly 40% on a simulated driving cycle (J. Bentley, A. D. Little, personal communication, April 1995). If waste heat from the fuel cell stack is used in the reformer, peak system efficiency can be improved to ~50% (J. Miller, Argonne Natl. Lab, personal communication, April 1995).

PEM fuel cells, now used in some experimental buses and cars, have made excellent progress in reducing their catalyst loading (usually platinum, which is the principal cost driver for PEMs) nearly to the same amount as is already in a car's catalytic exhaust converter—which fuel cells, of course, wouldn't need. PEMs are rapidly (and, to many, unexpectedly) approaching the targets of size, weight, and cost needed for production HEVs, and may well attain even quite ambitious targets through radically simplified mass-production techniques. Hand-assembled PEM cells today use machined metal plates with machined channels to support the electrodes and polymer membranes and to distribute the flows of fuel and oxidant. In contrast, proposed new techniques would stack flat polymer assemblies that have pre-molded channels, pre-loaded catalyst, and pre-embedded electrodes.

An unpublished Allison analysis for General Motors in 1994 found it plausible that this approach could cut PEMs' manufacturing costs by two orders of magnitude, to perhaps $47/kW. A cost even ten times higher would open up markets in stationary power generation such that very high production volumes, and hence further cost reductions, would follow. Low-cost PEMs therefore represent one of the biggest potential breakthroughs in energy conversion technology of any kind, whether for mobile or fixed applications. Although challenging and significant engineering lies ahead, there are no apparently insurmountable technical hurdles to overcome.

Despite the considerable development still needed, PEM fuel cells are entering the sphere of manufacturing engineering rather than basic research. For example, General Motors has comissioned Ballard Power Systems (a pioneering Vancouver, B.C. fuel cell developer) to make PEM cells with specific power of 500 W/kg, and 1 kW/kg stacks are already in the experimental stage (K. Dirks, personal communication, 18 January 1995).[14] Whether the very-low-cost-PEM approach can succeed should be known within a few years. If successful, manufacturing could occur soon and grow quickly. Its effects would be as revolutionary for stationary as for mobile power systems, each reinforcing the other.

Solid-oxide fuel cells are made with a completely different approach. Rather than operating at PEMs' ~80∞C, they combine the reactants at roughly 1,000°C in small channels running through a solid block of ceramic, with embedded metal electrodes and catalysts. Laboratory tests of single- or multi-layer cells confirm very high power densities; a plausible long-term target is that a ceramic block 15 cm on a side may ultimately be able to produce about 10 kW of electricity, running red-hot and presumably insulated by compact vacuum insulation. Such cells are also reversible (they can electrolyze their water product back into hydrogen and thereby store electrical energy), and are self-reforming, eliminating the often complex plumbing otherwise needed to break down liquid fuels into hydrogen. Results from early experiments suggest that these fuel cells can even directly "burn" some standard petroleum products.

The principal concern with high-temperature solid-oxide fuel cells is manufacturability. The internal structure of the block is quite complex, but must be made of ceramics that are typically very brittle. However, encouraging innovations are emerging at Allied Signal's Garrett Advanced Ceramics division near Los Angeles and at Idaho and Los Alamos National Laboratories. One of the most interesting is to use established mass-production techniques to make each specialized ceramic layer separately using a continuous process, then combine the layers and sinter them all together. With continued development, the prospect of commercial success with this approach should become clear within a few years.

MODELING

To explore all these ideas quantitatively, several simple bulk-parameter spreadsheets developed at RMI were used in combination with SIMPLEV (Cole, 1993b) for relatively comprehensive modeling of vehicle performance, fuel economy, and emissions approximations. Assumptions for principal vehicle parameters are outlined below. Itemized mass breakdown tables, road-load and performance calculation results, selected fuel economy sensitivities, and overall fuel economy and emissions estimates follow.

The SIMPLEV (Simple Electric Vehicle) program was developed at Idaho National Engineering Laboratory (INEL) for simulation of BEVs and HEVs on a variety of Federal and California State driving cycles. Our modeling with SIMPLEV used the Federal Urban Driving Cycle and the Federal Highway Fuel Economy Test Procedure.

SIMPLEV modeling of HEVs has been shown to correlate very closely with actual vehicle test data (Burke, 1994b) and the results of CarSim (Cuddy, 1995), a proprietary HEV

[14] This is only the stack mass. If the fuel is compressed gaseous hydrogen, then the mass overhead for auxiliary equipment such as the intake blower and cooling system, excluding the fuel tank(s), doubles the stack mass (or halves the specific power to ~500 W/kg) at system powers around 20–30 kW; this overhead becomes less favorable with smaller systems and more with larger systems. The specific power of these experimental fuel-cell systems is approaching the 830 W/kg threshold estimated necessary for direct competition with conventional internal-combustion engines and drive systems—that threshold is even lower for ultralight vehicles.

simulation program developed at AeroVironment (Los Angeles, CA) under contract for GM. Comparison of the two programs indicates that SIMPLEV modeling typically results in very slightly worse simulated fuel economy than CarSim (*ibid.*).

Each SIMPLEV run was corrected for change in the SOC of the LLD (ΔSOC) at the end of the driving cycle, since each simulation began with the LLD fully charged. The calculated correction was based on recharging the LLD back up to 100% SOC at the average driving-cycle efficiency of the APU/generator set. Gasoline fuel at a specific density of 740 g/l and energy density of 8,835 Wh/l was assumed.

The Rohde & Schilke model is a relatively simple bulk-parameter fuel economy model that simulates the EPA urban and highway driving cycles (Rohde & Schilke, 1981). It was originally developed at GM Systems Engineering for simulation of mechanical-flywheel/IC-engine hybrid vehicles, and does not include a correction for ΔSOC. For this reason, we have corrected its results to those of SIMPLEV and used it primarily to model convenient approximations of fuel economy sensitivity to changes in vehicle parameters.

Vehicle Mass

Vehicle curb mass was assumed to be 700 kg for the PNGV scenario and 520 kg for the Further Optimized scenario. Mass budgets for both scenarios follow this section. EPA test mass (M_{EPA}) including 136 kg for two occupants was used for road load calculations, and in the SIMPLEV and Rohde & Schilke fuel economy simulations. Acceleration and gradability performance modeling for the PNGV scenario used both M_{EPA} and gross mass including six 68-kg occupants and 91 kg of luggage.

To allow for the possible use of aluminum or combinations of composite reinforcements other than carbon fiber alone, and the realities of safety margins in composite parts that may not be of uniform thickness, our analysis assumed a 52% BIW mass reduction for the PNGV design scenario (not including the addition of special crash-energy-absorbing materials and structures to provide for collisions with significantly heavier collision partners). This conservatively assumes that much of the mass-saving advantage of polymer composites over aluminum (for the BIW with closures) might be given up to take advantage of lower-cost, high-volume production methods and less expensive low-pressure tooling with less precise control over part properties in non-critical areas. It also assumes that the 55% mass reduction projected by Ford (Gjostein, 1995b) for an aluminum BIW in the year 2000 may be the practical limit for meeting the PNGV criteria with metals. Additional materials and structures specifically for enhanced crash energy absorption are counted separately. With high-performance crash energy management included, the assumed BIW mass reduction for modeling is 45% if the 1995 MY Ford Taurus is used as the baseline. It should be kept in mind, however, that reduction of BIW mass by closer to the 67% achievable with carbon fiber (Eusebi, 1995; Gjostein, 1995b) may be more appropriate, providing that crashworthiness can still be not only maintained but improved, if it cuts the cost of performance-related components enough to offset any increase in materials and fabrication costs.

Modeling results indicate that once efficient regenerative braking (η_{regen} ~60%) is introduced as part of a hybrid electric drivesystem, fuel economy is not nearly as sensitive to vehicle mass, assuming all other variables are fixed, as to other factors such as APU efficiency. For example, if the baseline vehicle *test* mass is on the order of 800 kg, a 10% reduction in mass improves the composite city/highway fuel economy by only about 5% (~7% urban and ~4% highway). If, on the other hand, the APU/generator set efficiency were improved 10% from a 30% baseline average efficiency to 33%, the resultant fuel economy improvement is also about 10% for both urban and highway cycles.

Rolling Resistance

The rolling resistance coefficient was assumed to be 0.0072 for the PNGV design scenario and 0.0066 for the Further Optimized design scenario. (These numbers have been de-rated from lab-test tire rolling resistance coefficients of 0.0065 and 0.006, respectively, to account for the discrepancy between the SAE standard test and tires running on pavement.)

Aerodynamic Drag

We assumed a C_D of 0.20 for modeling the PNGV design scenario. Lowering only the C_D from the 1995 MY average of 0.33 to 0.2 cuts the drag at 60 mph by ~39%. When combined with a frontal area of 1.95 m^2, as compared to the 2.13 m^2 for the 1995 MY Ford Taurus as the CTL benchmark vehicle, the aerodynamic drag is reduced by a total of 45%. With a frontal area of 1.95 m^2 and a C_D of 0.20, the power consumed at the wheels by aerodynamic drag is just 4.54 kW at 60 mph. If, as in our further optimized design scenario, the frontal area is 1.75 m^2 and the C_D is 0.18, the aerodynamic drag load at the wheels drops to a mere 3.67 kW. Lowering the C_D by 10%, as an isolated variable, improves urban and highway fuel economy by about 3.5% and 6.5%, respectively, and composite city/highway economy by about 4.5%. A 45% reduction of aerodynamic drag improves highway fuel economy by up to about 29%—enough, given other improvements discussed, to reach at least the PNGV goal of tripled fuel economy. Dropping the C_D another 10% to 0.18, without changing the frontal area, either improves the fuel economy by another 5 mpg or allows other design elements to be optimized more for cost or packaging than for efficiency. It is important to note that a C_D well below 0.2, given that marketability can be maintained, is desirable because of not only its very significant contribution to highway fuel economy but also its effect on the size and cost of drivesystem components. This is particularly true for BEVs and HEVs, for which power-electronics costs go up significantly with maximum power-handling capacity, and becomes even more important as curb mass is further reduced.

Accessory Loads

For modeling purposes, we assumed a 250 W total *hotel* load (drivesystem auxiliaries are included in component efficiencies), equivalent to 25% of the CTL benchmark's estimated 1 kW annual average hotel load including air-conditioning (which can be momentarily as high as 2 kW in some conventional vehicles). Reduced HVAC requirements also contribute to the assumed C_D of 0.2, since a smaller refrigerant condenser would require less airflow, and thus smaller air inlets and outlets.

Series Hybrid Drivesystem

For the purpose of modeling, a single motor, reduction gear, and differential design was assumed. Although the use of multiple motors may turn out to be an overall advantage, we were unable to gather sufficient data for reasonably accurate modeling of such a design scenario. The same drivesystem component data sets were used for modeling both the PNGV and Further Optimized design scenarios, except that the latter assumed 47% less APU mass.

Efficiency maps for the General Electric (GE) 52 kW ETX-II permanent-magnet (PM) motor and controller were used as inputs for modeling. The efficiency data matrix for the ETX-II also correlate very closely with efficiency maps for the 53 kW Unique Mobility SR218 PM developed for the BMW-E1 electric vehicle (Eriksson, 1995), which actually has slightly higher specific power than the ETX-II system (Cole, 1993a). The SR218 also has better performance in automotive applications because the much broader range of peak power possible with Unique's phase advance technology (B. Rankin, Unique Mobility, personal communication, June 1995). Our use of the GE data is thus somewhat conservative.

The ETX-II components were designed to provide the 52 kW rated power at 150 VDC_{nom}, which is the voltage that was used in obtaining laboratory data supplied by INEL (Cole, 1993a). The higher 336–360-V_{nom} range that was used for our simulations would improve specific power and efficiency (*ibid.*). The data provided was also for the Darlington transistor (DT) controller, and not the MOS-controlled thyristor (MCT) version also developed for the ETX-II system. Based on limited test data, the MCT controller would provide an efficiency gain of 2–3 percentage points over the DT controller (*ibid.*). Because we did not attempt to compensate for these voltage and switch-type sensitivities, the motor and controller efficiencies for our simulations are actually lower than would be the case in a well designed application.

The ETX-II data were also used for the Further Optimized design scenario as nearly representative of more advanced components such as the SR218H PM motor and CA40-300L digital controller now in their final stages of development at Unique Mobility, Golden, CO. This new system from Unique Mobility, unlike the previously mentioned SR218 motor developed for BMW, is designed to operate in the 336-V_{nom} to 420-V_{max} range used for the simulations, which would as discussed above yield higher efficiency than represented by the ETX-II data. Its range of high efficiency is also significantly broader than that of the ETX-II (B. Rankin & K. Barnes, Unique Mobility, personal communication, June 1995). Complete data sets for this system were unfortunately not available in time for modeling.

The high gear segment of the TB-1 transaxle data matrix from dynamometer test results supplied by INEL was scaled slightly to simulate a single-speed transmission with a fixed 10:1 gear ratio.

The Stirling engine from Stirling Thermal Motors, Inc. (STM) was chosen for its high efficiency over a broad load range, low emissions, mechanical simplicity, appropriate packaging, and potentially low cost, as discussed in the previous section on APUs. The lower-cost all-metal version of the STM engine at 76 kg with a peak efficiency of 40% was selected for modeling the PNGV Design Scenario. Even with 90% engine mass and 25% packaging penalties relative to the all-metal version at 34% peak efficiency, this engine provided a substantial net gain in vehicle efficiency. Because the STM engine has very flat torque and efficiency curves, efficiency within three percentage points of peak is available over approximately 70% of the total load range. Very complete test data maps were made available for simulation of this engine.

Overall APU efficiency of 35% for the bulk-parameter models is based on the STM Stirling engine test data, with an optimized average of 38%, and 0.92 for the generator and controller on the mechanical APU output. The broad range of near-peak efficiency allows considerable load following and minimized on/off cycling. The control strategy for the APU averaged traction power requirements over 3 seconds to avoid fast transients. The minimum APU output was set at 9 kW.

The maximum continuous brake output of this engine is ~28.5 kW at 8,000 rpm. For bulk-parameter models the maximum output of the complete APU package was assumed to be 25.65 kW given a generator and power electronics with an average system efficiency of 90%. Maximum output for SIMPLEV simulations is determined by SIMPLEV's interpretation of the engine and generator efficiency matrix input files.

The Federal Urban Driving Schedule (FUDS) required the APU to turn on only three times during the 1,372 seconds (~23 minutes) of the simulation, despite the relatively small capacity of the LLD.

While the data for power and efficiency from STM are based on extensive testing, emissions data are based on a preliminary emissions index for 100%, 50%, and 25% of the maximum continuous engine output. The following input matrix file was used for SIMPLEV simulations:

Gasoline Engine APU File (could also use CNG, Diesel)
Fuel = 740 g/l and 8.835 kWh/l (83.76 g/kWh)
STM Stirling Engine and 12 liters gasoline
76 Engine mass (kg) (+8.9 kg fuel in "Vehicle" file)
28,235 Maximum continuous brake power at shaft (W)
0.0 0.0 HC, CO emissions at turn on (g)***
0.0 0.0 HC, CO emissions at turn off (g)***

$P_{fraction}$ (P_e/P_{max})	BSFC* (g/kWh)	HC** (g/kWh)	CO** (g/kWh)	NO_x** (g/kWh)
0.19	227	0.0001	0.02	0.458
0.27	211	0.0002	0.04	0.422
0.35	199	0.0015	0.06	0.335
0.44	190	0.0037	0.09	0.276
0.52	209	0.0075	0.13	0.234
0.60	209	0.0125	0.26	0.227
0.69	209	0.0185	0.39	0.221
0.77	190	0.0265	0.53	0.216
0.85	191	0.0395	0.67	0.211
0.94	193	0.0505	0.86	0.207
1.00	203	0.0609	1.02	0.203

*BSFC based on brake fuel efficiency test data, with
0.40 η_{max} = 209 g/kWh
**Emissions figures are calculated using an Emissions Index that was derived from laboratory tests at STM.
***No data were yet available for cold- or hot-start emissions. Although the small, external, continuous-combustion burner for the Stirling engine should produce very little emissions under such circumstances, it is not clear just how little.

An ultracapacitor pack was chosen for the LLD based on availability of data for devices that meet the power, mass, and packaging requirements for lightweight series HEVs. For the Further Optimized design scenario, the mass of the ultracapacitor pack was reduced from 63 kg to 20 kg to simulate a 600-Wh flywheel LLD, assuming the efficiencies would be similar (Burke, 1995b; Post & Post, 1993)

The following data are typical of the current organic-electrolyte ultracapacitor cells being developed at Maxwell Laboratories (Burke, 1995b; Trippe, *et al*., 1993):

- Specific capacitance = 0.75 F/cm^2
- Specific resistance = 1–2 Ω/cm^2
- Voltage = 3 V @ 100% SOC
- Specific energy = 6–7 Wh/kg

- Specific power = 2–4 kW/kg

The ultracapacitor LLD specifications used for the PNGV Design Scenario were:

- 140 3-V, 1.5-Ah cells for 420 V maximum, 210 V minimum, and 315 V nominal DC bus voltages.
- Pack mass @ 0.45 kg per cell = 63 kg (ancillaries are included with the SIMPLEV "vehicle" mass of 519 kg).
- Total pack capacity = 630 Wh (based on 2 Ah/cell @ 2.25 V nominal).
- Usable capacity* = 472.5 Wh (limited by the 210-V minimum for the motor and LLD power electronics) (V/V rated as an ideal capacitor for modeling) .
- Peak power available for acceleration or regenerative braking ≥ 63 kW (actually limited to 52 kW by the ETX-II motor and controller data used in the simulations)
- Average internal resistance of 2 Ω/cm^2, divided by 3,200 cm^2/cell for 2,400 F cells at 0.75 F/cm^2 is equal to 6.25 ¥ 10^{-4} Ω/cell, based on the high value from the 1–2 Ω/cm^2 range of test results for the organic electrolyte cells from Maxwell Laboratories.
- A Puekert exponent of -0.0022, as used by A. Burke for similar SIMPLEV simulations.

* The usable capacity of the 630-Wh pack of 140 3-V, 1.5-Ah cells, given $V_{min} = 0.5\ V_{max}$, is 472.5 Wh, because by the time the voltage reaches 50%, the energy withdrawn will be 75% of the total capacity. Given the PNGV design scenario discussed, this would be enough to provide 40.5 seconds of maximum acceleration without any help from the 24-kW APU or charge from regenerative braking. This equates to four and one-half 0–60 mph accelerations in 8.9 s at EPA test weight, and three 0–60 mph accelerations in 12.9 s at gross weight (both on a level road), or two accelerations 0–60 mph in 19 s at gross weight on a 6% grade (gross weight includes six 68-kg passengers and 91 kg luggage).

Because sufficient data to characterize electro-chemical batteries with high specific power or flywheel LLDs were unavailable, we chose not to include modeling results for these options. Input files based on very limited data and many assumptions about the trade-offs inherent in these technologies produced simulation results that were within 5% of the results using more detailed data for ultracapacitors.

SIMPLEV Input Summary:
Vehicle test mass: 836 kg (PNGV) 656 kg (Further Opt.)
Frontal Area: 1.95 m^2 (PNGV) 1.75 m^2 (Further Opt.)
Drag Coefficient: 0.20 (PNGV) and 0.18 (Further Opt.)
Air density: 0.002266 $slugs/ft^3$ (0.000938 kg/m^3)
Coastdown C_0 (r_0): 0.0072 (PNGV), 0.0066 (Further Opt.)
Coastdown C_1 (r_1): 5.00E-06 sec/ft
Accessory load: 250 W
ETX-II Inverter (Speed ¥ 1.00, Torque ¥ 0.80)
Min. voltage: 210 V
Max. current: 380 A
ETX-II Motor (Speed ¥ 1.00, Torque ¥ 0.80):
Max. Speed = 11,000 rpm
Max. Power = 42 kW
Power fraction available at wheels for regen braking: 0.75
TB-1 Transaxle (High gear only):
Speed ¥ 1.22, Torque ¥1.80, Gear ratio: 10:1
Ultracapacitor Simulation LLD: 140 cells (63 kg)
STM Stirling APU, Gasoline fuel, No catalytic converter
Max. engine output: 28.235 kW
UNIQ PM SR180LC generator
Max. output: 24.000 kW, Min. output: 9.000 kW
On at 45.0% DOD, Off at 15.0% DOD
Traction power averaged over: 3 sec.

SIMPLEV Simulation of the PNGV Design Scenario:

Federal Urban Driving Schedule
96 mpg (41 km/l or 2.45 l/100 km)
Corrected for 40.5% ΔSOC, recharged @ 38% APU η and 92% alternator η.

Power, current, and voltage for load leveling device (LLD).

Vehicle speed, motor power, inverter efficiency, motor efficiency, and transmission efficiency.

NOTE: The same motor, inverter, and transmission map input matrix files were used for all design scenarios.

SIMPLEV Simulation of the PNGV Design Scenario:

Highway Fuel Economy Test Procedure
91 mpg (39 km/l or 2.58 l/100 km)
Corrected for 27.4% ΔSOC, recharged @ 38% APU η and 92% alternator η.

Power, current, and voltage for load leveling device (LLD).

Vehicle speed, motor power, inverter efficiency, motor efficiency, and transmission efficiency.

SIMPLEV Simulation of PNGV Design Scenario:

Federal Urban Driving Schedule

FINAL RESULTS OF FUDS SIMULATION
(FUDS.CYC), Dt = 1.0 sec.:
Using bulk file: PNGV_U.BLK
Maximum battery power................22.4 kW (64 A @ 347 V)
Average battery current (A)........13.0 dis. 17.0 chg. 2.1 net
Average battery power (kW).......3.9 dis. 5.0 chg. 0.7 net
Ampere-hours discharged.......................................3.2 Ah
Ampere-hours charged...2.4 Ah
Effective battery capacity.......................................2.0 Ah
Net battery energy...0.3 kWh
Gross battery energy out.......................................1.0 kWh
Energy supplied by APU......................................0.6 kWh
Energy supplied by regen.....................................0.2 kWh
Electrical energy supplied to wheels........................1.0 kWh
Percent of energy supplied by regen..........................24.7%
Average battery efficiency...........99.2% disch., 99.2% chrg.
Average inverter efficiency.........90.4% driving, 88.6% regen
Average motor efficiency...........92.8% driving, 92.7% regen
Average transmission efficiency..88.9% driving, 89.2% regen
Average powertrain efficiency.....74.5% driving, 73.3% regen
APU energy economy....................85.0 Wh/mi52.9 Wh/km
Net traction energy economy........107.4 Wh/mi, 66.8 Wh/km
Net battery energy economy..........35.2 Wh/mi, 21.9 Wh/km
Gross battery energy economy......128.7 Wh/mi, 80.0 Wh/km
Maximum battery power density......780.6 W/lb, 354.8 W/kg
Average speed...................................19.5 mph, 31.4 km/h
Total distance traveled..............................7.5 mi, 12.0 km
Vehicle "driving" time....................0.381 hours (1373 sec.)
Number of cycles completed...1
Depth-of-discharge..40.5 %
Battery voltage...249.8 V
Battery current...1.0 A

Emissions:

HC: 0.001 g	0.000 g/mi	0.000 g/km
CO: 0.047 g	0.006 g/mi	0.004 g/km
NO_x: 0.232 g	0.031 g/mi	0.019 g/km

Gasoline fuel used: 0.211 liters 56.94 km/l

Corrected for ΔSOC: 0.294 liters total
40.87 km/l
2.45 l/100 km
96 mpg

Highway Fuel Economy Test Procedure

FINAL RESULTS OF FEDERAL HIGHWAY CYCLE
SIMULATION (HIWAY.CYC), Dt = 1.0 sec.:
Using bulk file: PNGV_H.BLK
Maximum battery power................16.5 kW (56 A @ 293 V)
Average battery current (A)........19.0 dis. 13.6 chg. 0.9 net
Average battery power (kW).......5.9 dis. 4.0 chg. 0.9 net
Ampere-hours discharged.......................................2.0 Ah
Ampere-hours charged...1.5 Ah
Effective battery capacity.......................................2.0 Ah
Net battery energy...0.2 kWh
Gross battery energy out.......................................0.6 kWh
Energy supplied by APU......................................1.1 kWh
Energy supplied by regen.....................................0.1 kWh
Electrical energy supplied to wheels........................1.4 kWh
Percent of energy supplied by regen..........................15.4%
Average battery efficiency...........99.2% disch., 99.3% chrg.
Average inverter efficiency.........89.5% driving, 90.5% regen
Average motor efficiency...........87.2% driving, 90.2% regen
Average transmission efficiency..86.5% driving, 87.8% regen
Average powertrain efficiency.....67.5% driving, 71.7% regen
APU energy economy.................109.5Wh/mi, 68.0 Wh/km
Net traction energy economy........123.1 Wh/mi, 76.5 Wh/km
Net battery energy economy..........18.8 Wh/mi, 11.7 Wh/km
Gross battery energy economy.......60.7 Wh/mi, 37.7 Wh/km
Maximum battery power density......574.6 W/lb, 261.2 W/kg
Average speed...................................48.2 mph, 77.6 km/h
Total distance traveled.............................10.3 mi, 16.5 km
Vehicle "driving" time.......................0.213 hours (766 sec.)
Number of cycles completed...1
Depth-of-discharge..27.4 %
Battery voltage..305 V
Battery current...0.8 A

Emissions:

HC: 0.003 g	0.000 g/mi	0.000 g/km
CO: 0.096 g	0.009 g/mi	0.006 g/km
NO_x: 0.395 g	0.038 g/mi	0.024 g/km

Gasoline fuel used: 0.369 liters 44.75 km/l

Corrected for ΔSOC: 0.425 liters total
38.83 km/l
2.58 l/100 km
91.3 mpg

SIMPLEV Simulation of the Further Optimized Design Scenario
with frontal area, C_D, curb mass, and r_0 vehicle parameters modified as noted in the text, mass budgets, and road load calculation tables,and using the PNGV Design scenario drivesystem including the STM Stirling Engine at 40% peak efficiency, but with APU efficiency achieved by substitution of ceramics on the hot side of the engine, reducing its mass by 40%:

Federal Urban Driving Schedule
128 mpg (54.5 km/l or 1.83 l/100 km)
Corrected for 41.2% ΔSOC, recharged @ 38% APU η and 92% alternator η.

Power, current, and voltage for load leveling device (LLD).

Highway Fuel Economy Test Procedure
98 mpg (42 km/l or 2.4 l/100 km)
Corrected for 11.6% ΔSOC, recharged @ 38% APU η and 92% alternator η.

SIMPLEV Simulation of Further Optimized Design Scenario

Federal Urban Driving Schedule

FINAL RESULTS OF FUDS SIMULATION
(FUDS.CYC), Dt = 1.0 sec.:
Using bulk file: PNGV_OPU.BLK
Maximum battery power................18.0 kW (70 A @ 257 V)
Average battery current (A)........10.1 dis. 14.6 chg. 2.2 net
Average battery power (kW).......3.1 dis. 4.3 chg. 0.7 net
Ampere-hours discharged.......................................2.6 Ah
Ampere-hours charged...1.8 Ah
Effective battery capacity.......................................2.0 Ah
Net battery energy...0.3 kWh
Gross battery energy out.......................................0.8 kWh
Energy supplied by APU......................................0.4 kWh
Energy supplied by regen.....................................0.2 kWh
Electrical energy supplied to wheels........................0.8 kWh
Percent of energy supplied by regen...........................29.1%
Average battery efficiency...........99.4% disch., 99.2% chrg.
Average inverter efficiency.........89.5% driving, 88.6% regen
Average motor efficiency...........91.9% driving, 92.7% regen
Average transmission efficiency..88.7% driving, 89.2% regen
Average powertrain efficiency.....73.0% driving, 73.2% regen
APU energy economy....................54.9 Wh/mi34.1 Wh/km
Net traction energy economy...........78.1 Wh/mi48.5 Wh/km
Net battery energy economy............36.0 Wh/mi22.4 Wh/km
Gross battery energy economy..........107.4 Wh/mi66.8 Wh/k
Maximum battery power density ....: 628.4 W/lb285.6 W/kg
Average speed....................................19.5 mph 31.4 km/h
Total distance traveled..............................7.5 mi 12.0 km
Vehicle "driving" time.....................0.381 hours (1373 sec.)
Number of cycles completed..1
Depth-of-discharge..41.2 %
Battery voltage..247.0 V
Battery current..1.0 A

Emissions:

HC:	0.001 g	0.000 g/mi	0.000 g/km
CO:	0.029 g	0.004 g/mi	0.002 g/km
NOx	0.151 g	0.020 g/mi	0.013 g/km

Gasoline fuel used: 0.136 liters (88.01 km/l)

Corrected for ΔSOC: 0.220 liters total
54.53 km/l
1.83 l/100 km
128 mpg

Highway Fuel Economy Test Procedure

FINAL RESULTS OF FEDERAL HIGHWAY CYCLE SIMULATION (HIWAY.CYC), Dt = 1.0 sec.:
Using bulk file: PNGV_OPH.BLK
Maximum battery power................11.2 kW (36 A @ 310 V)
Average battery current (A)........14.8 dis. 13.9 chg. 1.1 net
Average battery power (kW)......4.6 dis. 4.2 chg. 0.4 net
Ampere-hours discharged.......................................1.6 Ah
Ampere-hours charged...1.4 Ah
Effective battery capacity.......................................2.0 Ah
Net battery energy...0.1 kWh
Gross battery energy out.......................................0.5 kWh
Energy supplied by APU......................................1.0 kWh
Energy supplied by regen.....................................0.1 kWh
Electrical energy supplied to wheels........................1.1 kWh
Percent of energy supplied by regen...........................18.0%
Average battery efficiency...........99.4% disch., 99.3% chrg.
Average inverter efficiency.........88.5% driving, 90.5% regen
Average motor efficiency...........85.4% driving, 90.3% regen
Average transmission efficiency..86.3% driving, 87.8% regen
Average powertrain efficiency.....65.2% driving, 71.6% regen
APU energy economy.................96.5 Wh/mi, 60.0 Wh/km
Net traction energy economy........99.9 Wh/mi, 62.1 Wh/km
Net battery energy economy............8.6 Wh/mi, 5.3 Wh/km
Gross battery energy economy......50.1 Wh/mi, 31.1 Wh/km
Maximum battery power density...........392 W/lb, 178 W/kg
Average speed..................................48.2 mph, 77.6 km/h
Total distance traveled...........................10.3 mi, 16.5 km
Vehicle "driving" time.....................0.213 hours (766 sec.)
Number of cycles completed..1
Depth-of-discharge..11.6 %
Battery voltage..371 V
Battery current..0.7 A

Emissions:

HC:	0.002 g	0.000 g/mi	0.000 g/km
CO:	0.074 g	0.007 g/mi	0.004 g/km
NOx:	0.357 g	0.035 g/mi	0.022 g/km

Gasoline fuel used: 0.327 liters (50.44 km/l)

Corrected for ΔSOC: 0.396 liters total
41.7 km/l
2.4 l/100 km
98 mpg

CONCLUSIONS

It appears very unlikely that the PNGV goal of tripled fuel economy can be met by incremental improvements to conventional automotive technologies. Even with the very plausible 15–20% mass reductions for optimized steel car bodies, an incremental approach would probably fall significantly short without extremely low-drag vehicle design and unforeseen gains in the efficiency of spark-ignition internal combustion engines. However, artfully combining new materials, reasonable platform design improvements, *and* carefully optimized hybrid drivesystems appears to have the potential for not only meeting but exceeding PNGV goals within the prescribed time frame. Thus using a less familiar "leapfrog" approach to achieve tripled or even better fuel economy may be easier and quicker than the smaller gains available from incrementalism.

While simultaneously introducing many kinds of technologies and design improvements implies higher levels of perceived risk and manufacturing investment shift, the synergistic relationships between some of the constituent technologies appear to require their introduction as a system, rather than separately. One appropriate strategy would be early introduction of the platform design improvements, such as markedly reducing aerodynamic drag and rolling resistance. By lowering peak and continuous power requirements, these improvements would then permit much more practical and attractive hybrid drivesystems. (This assumes that cost, size, and mass will remain limiting factors for hybrid-electric drive components as a function of peak power requirements. If this assumption were nullified by unforeseen developments, the manufacturer would be free to introduce the new technologies from any starting point.)

Modeling suggests that based on tested technologies that already exist but may not yet be production-ready, 80–90 mpg can be achieved very flexibly via numerous variations on the general vehicle-design, component-selection, and control-strategy recommendations in this analysis. It may well be practical, by carefully matching technologies and control strategies, to produce very attractive vehicles that meet all PNGV criteria *and* get about 100 mpg or better on urban and highway driving cycles (see SIMPLEV simulations). If automakers apply this approach to somewhat smaller cars with ample seating for four to five occupants rather than five to six, while meeting all other PNGV criteria, then achieving over 100 mpg becomes reasonable. To the degree that plausible further technological progress is made, however, fuel economy well in excess of 100 mpg could be feasible for vehicles meeting *all* of the PNGV design criteria. This would depend on continued improvement and low-load optimization of materials and propulsion systems technologies (rather than engineering them for mass-production automotive applications only at current levels of component performance and only for the high power requirements of current platforms).

The analysis reflected in this paper was clearly a first pass at applying whole-systems design to meeting the PNGV goal of tripled fuel economy. There is thus room for much more thorough optimization of component matching and control strategy optimization. Further research with this relatively comprehensive approach should yield considerably more refined understanding of system optimization and of sensitivities to component and multi-variate parameter changes.

While emissions requirements and fuel economy goals tend to suggest the use of battery-electric vehicles or hybrids with long combustion-free range, those vehicles will probably have to be ultralight to be successful, and hybrid-electric to be ultralight. This favors APU-electric hybrids with very small electrical energy storage capacity for load leveling, rather than range-extenders. Preliminary research at Rocky Mountain Institute suggests that some APU-electric hybrids will be able to meet the VZEV ("Virtual Zero-Emission Vehicle") alternative compliance path proposed by the California Air Resources Board (CARB, 1995).

Mass, cost, and complexity compound in heavy hybrids, but decompound in light hybrids. Desirable levels of mass reduction are determined mainly by the need to reduce cost and complexity while improving fuel economy *and* performance, rather than by fuel economy alone. Because mass decompounding is non-linear and discontinuous, there is no simple calculation or design space to describe it. Given a fixed payload capacity, the mass decompounding factor that relates primary and secondary units saved gets smaller and smaller (iterated over recursive re-optimizations), until absolute and specific power requirements become small enough to make hybrid drivesystems attractive (as opposed to the hybrid drive's adding mass, cost, and complexity). The decompounding factor then rebounds with hybridization of the vehicle, providing opportunities for further mass savings.

Whole-systems design and engineering from the outset, with meticulous attention to details such as accessory loads, brake drag, and wheel bearing friction, is necessary for successful optimization. Every platform parameter and component of the drivesystem must be optimized as part of the whole system if the design is to be successful. The net marginal cost per vehicle is then likely to be negative, as more should be saved on components than is needed to amortize more thorough and integrative engineering and design.

This potential shift towards holism in automotive design is analogous to a phenomenon recently observed in superefficient lighting, motors, buildings, and other technical systems (Lovins, 1994): initially, as savings are increased they become more costly, but when a sufficient level of savings is reached, the design "tunnels through the cost barrier" by downsizing, simplifying, or eliminating some equipment, or by otherwise achieving multiple benefits from a single expenditure. This appears to be possible also in automotive design (Lovins, 1995), and to offer practical scope for realizing Einstein's ideal that "everything should be made as simple as possible—but not simpler." Capturing the resulting design synergies may constitute the central technological and cultural challenges to the automotive industry for the rest of this decade and beyond.

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REFERENCES

Allied Signal Aerospace 1993: "Hybrid Vehicle Power Unit," technical literature hand-out at the 1993 SAE International Congress and Exposition, 1–5 March.

American Automobile Manufacturers' Association (AAMA) 1994: *AAMA Motor Vehicle Facts & Figures*, American Automobile Manufacturers' Association (Washington DC).

American Iron and Steel Institute 1994: "Holistic Design With Steel For Vehicle Weight Reduction" (Southfield MI), February.

American Iron and Steel Institute 1995: "Steel's Potential to Meet the PNGV Goals" (Southfield MI).

Anderson, Catherine and Erin Pettit 1995: *The Effects of APU Characteristics on the Design of Hybrid Control Strategies for Hybrid Electric Vehicles*, SAE 950493, Society of Automotive Engineers Inc. (Warrendale PA), 27 February.

Ashley, S. 1994: "Auto Engine to Use NASP Materials," *Mechanical Engineering*, October, p. 24.

Automotive Engineering 1992: "Battery and Electric Vehicle Update," *Automotive Engineering*, pp. 17–20, September.

Bennethum, James E., Thomas D. Laymac, Lennart N. Johansson, Ted M. Godett 1991: "Commercial Stirling Engine Development and Applications," *SAE Technical paper series*, Portland, Oregon, August.

Blake, R. J. and Lawrenson, P. J. 1992: "New Applications of Very Large and Small Switched Reluctance Drives," 4.4.1, *Proc. Power Conversion and Intelligent Motion*, Nürnberg, April.

BMW 1991: "Losses within the overall energy chain," presented at the OTA Workshop on Advanced Automotive Technologies (Washington DC), 19–20 April.

Borroni-Bird, Christopher E. and Janet Osteryoung 1995: "Energy Conversion Materials and Processes," *from Proc. of the Basic Research Needs for Vehicles of the Future* (Princeton NJ), pp. 11–17.

Burke, A.F. 1991: *Battery Availability for Near-Term (1998) Electric Vehicles*, SAE 911914, Society of Automotive Engineers Inc. (Warrendale PA).

Burke, Andrew F. 1994a: "The Potential of Electrochemical Capacitors for Electric and Hybrid Vehicle Applications," *S/EV94 Sustainable Transportation Conference* (Providence RI), 3–5 October.

Burke, Andrew F. 1994b: "Dynamometer and Road Testing of Advanced Electric Vehicles and Projection of Future Range Capability," *Proc. of the 12th International Electric Vehicle Symposium (EVS-12)* (Anaheim CA), pp. 807–815.

Burke, Andrew F. 1995: "Electric/Hybrid Super Car Designs Using Ultracapacitors," paper presented at the 30th IECEC Meeting (Orlando FL), August.

California Air Resources Board (CARB) 1995: *ARB Staff Proposal for Allowing Hybrid-Electric Vehicles to Receive Zero-Emission Vehicle Credit*, California Air Resources Board (El Monte CA), 10 April.

Cole, G. H. 1993a: *Comparison of the Unique Mobility and DOE-Developed AC Electric Drive Systems*, EG&G Idaho, Inc. (Idaho Falls ID), January.

Cole, G. H. 1993b: *SIMPLEV: A Simple Electric Vehicle Simulation Program*, EG&G, Inc. (Idaho Falls ID), April.

Cuddy, Matthew 1995: "A Comparison of Modeled and Measured Energy Use in Hybrid Electric Vehicles," *1995 SAE International Congress and Exposition* (Detroit MI), National Renewable Energy Laboratory, 27 February–3 March.

DaimlerBenz 1995: *Forschung und Technik*, presented at the OTA Workshop on Advanced Automotive Technologies (Washington DC), 19–20 April.

Demmler, A. 1994: "Quad-4 Plastic Water Outlet," *Automotive Engineering*, November, p. 51.

Eriksson, Sture 1995: "Drive systems with permanent magnet synchronous motors," *Automotive Engineering*, February.

Eusebi, E. 1995: "Composite Intensive Vehicles: Past, Present and Future" remarks from address at the *Vice President's Symposium on Structural Material Challenges for the PNGV* (Washington DC), 22-23 February.

Fraas, L.M., P.E. Gruenbaum, *et al*. 1993: "GaSb IR Solar Cells with Improved Efficiency and Manufacturability," submitted to 23rd IEEE Photovoltaic Specialists Conference, May.

Gawronski, Francis J. 1992: "Natron reinvents HVAC for the 90's," *Automotive Industries' Insider*, p. 3, 1 May.

General Motors 1990: "Impact: Goodyear Designs Special Tires for the GM Electric Car," press release.

General Motors 1992: "General Motors Impact Electric Vehicle," press package.

Gjostein, N.A. 1995a: "Technology Needs Beyond PNGV," remarks from address at the Basic Research Needs for Vehicles of the Future (New Orleans LA), 5 January.

Gjostein, N.A. 1995b: "PNGV Material R&D Roadmap," remarks from address at the *Vice President's Symposium on Structural Material Challenges for the PNGV* (Washington DC), 22–23 February.

Harbison, W. 1993: "Coatings for Plastic Glazing," *Automotive Engineering*, pp. 24-28, May.

Hendershot, James R., Jr. 1991: "A Comparison of AC, Brushless & Switched Reluctance Motors," *Motion Control*, pp. 16–20, April.

Hobbs, C. Adrian 1995: *Dispelling the Misconceptions about Side Impact Protection*, SAE 950879, Society of Automotive Engineers Inc. (Warrendale PA), 27 February–2 March.

Hopkins, Dr. D., M. Rubin, and Dr. D. Arasteh 1994: "Smart Thermal Skins for Automobiles," *Proc. of the Dedicated Conference on Supercars (Advanced Ultralight Hybrids)*, ISATA (International Symposium on Advanced Transportation Applications) (Aachen,Germany), pp. 667–674, 31 October–2 November.

Horvath, John 1994: "Brushless Motors: The Best of DC and AC," *Electrical Design & Mfg.*, p. 19, November/December.

Houghton, David J., PE, Robert C. Bishop, Amory B. Lovins, Bristol L. Stickney, James J. Newcomb, Michael

Shepherd, and Bradley J. Davids, PE 1992: *Space Cooling Technology Atlas*, E SOURCE (Boulder CO).

Howard, Geoffrey 1986: *Automobile Aerodynamics*, Osprey Publishing Limited (London).

Kindervater, Dr. C.M. 1994: "Crash Resistance and Strength of High Performance Composite Light Vehicle Substructures," *Proc. of the Dedicated Conference on Supercars (Advanced Ultralight Hybrids)*, ISATA (International Symposium on Advanced Transportation Applications) (Aachen,Germany), pp. 741–751, 31 October–2 November.

Krenkel, W. 1994: "CMC Materials for High Performance Brakes," *Proc. of the Dedicated Conference on Supercars (Advanced Ultralight Hybrids)*, ISATA (International Symposium on Advanced Transportation Applications) (Aachen,Germany), pp. 769–775, 31 October–2 November.

Lovins, Amory B. 1994: "If You Think Education is Expensive, Try Ignorance," presented at the E SOURCE Corporate Energy Managers' Roundtable, 6 June.

Lovins, Amory B. 1995a: "Advanced Ultralight Hybrids: Necessity and Practicality of a Leapfrog," remarks from address at the *Vice President's Symposium on Structural Material Challenges for the PNGV* (Washington DC), 22-23 February, RMI publication T95–18, Rocky Mountain Instittute (Snowmass CO).

Lovins, Amory B. 1995b: "Supercars: Advanced Ultralight Hybrid Vehicles," *Encyclopedia of Energy Technology and the Environment* (first edition), Wiley-Interscience.

Lovins, Amory B., Michael M. Brylawski, David R. Cramer, Ian Jay Czaja, and Timothy C. Moore 1995: *Hypercars: Materials and Policy Implications*, Rocky Mountain Institute (Snowmass CO).

Lovins, Amory B. and Bill Howe 1992: "Switched Reluctance Motor Systems Poised for Rapid Growth," *Tech Update*, E SOURCE (Boulder CO), November.

Lovins, Amory B. and L. Hunter Lovins 1995: "Reinventing the Wheels," *The Atlantic Monthly*, pp. 75–86, January.

Luck, R. 1994: "Splitting the Cycle," *Australian Road & Track*, Autumn, pp. 24–27.

Lundell, Björn, Mikael Edvardsson, Lennart Johansson, Johnny Korner, and Stig Pilhall 1995: *SIPSBAG—The Seat-Mounted Side Impact Airbag System*, SAE 950878, Society of Automotive Engineers Inc. (Warrendale PA), 27 February–2 March.

MacKay, Robin 1993: *Hybrid Vehicle Gas Turbines*, SAE 930044, Society of Automotive Engineers Inc. (Warrendale PA), 1–5 March.

Mangin, C., J. Neely III, and J. Clark 1993: "The Potential for Advanced Ceramics in Automotive Engine Applications," *Journal of Materials*, June, pp. 23–27.

Mariano, Stephen A., Floyd R. Tuler, and Walter S. Owen 1993: "Comparing Steel and Aluminum Auto Structures by Technical Cost Modeling," *Journal of Materials* **45**(6):20–22, June.

Martin, C. 1994: "Future Power Engine: A Revolutionary Concept by Newbold & Associates," *Key Solutions* **3**(5):15–17, September.

MMCC, Inc. 1994: "Materials for the 21st Century," materials performance and applications update published by the manufacturer, October, pp. 1–5, Metal Matrix Cast Composites, Inc. (Waltham, MA).

Musikant, S., W. Chiu, D. Darooka, D.M. Mullings, and C.A. Johnson 1985: "Ceramic Automotive Stirling Engine Study" *General Electric Company,* (Philadelphia, PA) January.

National Safety Council 1991: "Accident Facts," 1991 Edition.

Niederer, Peter F., Felix H. Walz, Robert Kaeser, and Anton Brunner 1993: *Occupant Safety of Low-Mass Rigid-Belt Vehicles*, SAE 933107, Society of Automotive Engineers Inc. (Warrendale PA), 8–10 November.

Niederer, Peter F., Robert Kaeser, Felix H. Walz, and Eberhard Faerber, undated: "Compatibility Considerations for Low-Mass Rigid-Belt Vehicles," *Accident Prevention & Analysis*, preprint manuscript.

Office of Technology Assessment (OTA) 1995: *Advanced Automotive Technologies: Draft Report on Technologies and Vehicle Systems*, draft copy, U.S. Congress (Washington DC), 14 April.

Partnership for a New Generation of Vehicles (PNGV) 1994: *Program Plan*, 27 July.

Post, R., T. Fowler, and S. Post 1993: "A High-Efficiency Electromechanical Battery," *Procs. IEEE* **81**(3):462–474, March.

Prescott, Roger 1995: "The Future of the Carbon Fiber Industry—Specialty or Commodity?" *Proc. of the 40th International SAMPE Symposium* (Anaheim CA), pp. 994–997, 8–11 May.

Riley, Robert Q. 1994: *Alternative Cars in the 21st Century*, Society of Automotive Engineers, Inc. (Warrendale PA).

Rohde, Steve M., and Neil A. Schilke 1981: *The Fuel Economy Potential of Heat Engine/Flywheel Hybrid Vehicles*, SAE 810264, Society of Automotive Engineers Inc. (Warrendale PA).

Ruderman, M.A., T. Juergens, and R. Nelson 1994: "A New High Rate, Fast Charge, Sealed Lead Acid Battery," *Proc. of the Dedicated Conference on Supercars (Advanced Ultralight Hybrids)*, ISATA (International Symposium on Advanced Transportation Applications) (Aachen,Germany), pp. 121–127, 31 October–2 November.

Seal, M. and L. Fraas 1994: "A Thermo-photovoltaic Generator for Use in a Lightweight Electric Car," project proposal to the U.S. Department of Energy, Vehicle Research Institute, Western Washington University (Bellingham WA), pp. 4–22.

Seal, M.R. and M. Fitzpatrick 1982: "A Lightweight Two-Passenger Automobile Combining Improved Crashworthiness, Good Performance, and Excellent Fuel Economy," Vehicle Research Institute, Western Washington University (Bellingham WA).

Sherman, A.M. 1995: "Future Research for Aluminum Vehicle Structure," January.

Sperling, D and A.F. Burke 1994: *Hybrid Electric Vehicles: Always Second Best?*, Electric Power Research Institute (EPRI) (Palo Alto CA), July.

Stirling Thermal Motors 1995: Engine Performance Test Data at Sterling Thermal Motors (275 Metty Drive, Ann Arbor MI 48103).

Switched Reluctance Drives Ltd. 1991: *Switched Reluctance Drives for Electric Vehicle Propulsion*, Switched Reluctance Drives Ltd. (Leeds UK), March.

Therén, Kjell and Anders Lundin 1990: "Advanced Composite Materials for Road Vehicles," *Materials & Design* **11**(2):71–74, April.

Trippe, Anthony P., Burke, Andrew F., and Blank, Edward 1993: *Improved Electric Vehicle Performance with Pulsed Power Capacitors*, SAE 931010, Society of Automotive Engineers Inc. (Warrendale PA), 1–5 March.

USMC 1994: "Nylon Heat Exchangers," *USMC Technology Transfer*, U.S. Marine Corps.

Volvo Car Corporation 1992: *Volvo ECC: A Volvo Environmental Concept Car*, press literature (Göteborg, Sweden).

West, John G. W. 1994: " DC, induction, reluctance and PM motors for electric vehicles," *Power Engineering Journal*, pp. 77–88, April.

Williams, Robert H. 1993: "Fuel Cells, Their Fuels, and the U.S. Automobile," Princeton University, Center for Energy and Environmental Studies paper prepared for The First Annual World Car 2001 Conference (Riverside CA).

Wood, Geoff 1994: Address to 1994 ISATA Conference (Aachen, Germany), 31 October–2 November.