Speeding The Transition: Designing A Fuel-Cell Hypercar

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Presented to the National Hydrogen Association's 8th Annual U.S. Hydrogen Meeting (Alexandria VA), 11-13 March 1997.

ABSTRACT

A rapid transformation now underway in automotive technology could accelerate the transition to transportation powered by fuel cells.

Ultralight, advanced-composite, low-drag, hybrid-electric "hypercars™"—using combustion engines—could be three- to fourfold more efficient and one or two orders of magnitude cleaner than today's cars, yet equally safe, sporty, desirable, and (probably) affordable. Further, important manufacturing advantages—including low tooling and equipment costs, greater mechanical simplicity, autobody parts consolidation, shorter product cycles, and reduced assembly effort and space—permit a free-market commercialization strategy.

This paper discusses a conceptual hypercar powered by a proton-exchange-membrane fuel cell (PEMFC). It outlines the implications of platform physics and component selection for the vehicle's mass budget and performance.

The high fuel-to-traction conversion efficiency of the hypercar platform could help automakers overcome the Achilles' heel of hydrogen-powered vehicles: onboard storage. Moreover, because hypercars would require significantly less tractive power, and even less fuel-cell power, they could adopt fuel cells earlier, before fuel cells' specific cost, mass, and volume have fully matured. In the meantime, commercialization in buildings can help prepare fuel cells for hypercars.

The promising performance of hydrogen-fueled PEMFC hypercars suggests important opportunities in infrastructure development for direct-hydrogen vehicles.

I. INTRODUCTION

The magnitude and severity of the impacts of burning petroleum products in vehicles range through all geographic scales, from local air quality to global climatic change, and require an understanding of many disciplines, from the natural sciences to health and welfare to national security, and beyond. Outstripping human population growth, global growth in transportation and demand for vehicles will continue as incomes rise and the majority of the world eyes OECD levels of mobility. Accommodating the equitable desires of non-OECD peoples with a petroleum-based transport system is clearly not sustainable. Further, even with rapid growth outside of the OECD, the magnitude of petroleum use by transportation inside the OECD will command the lion's share for decades to come.

All of this presents a chasm of challenges for transportation technology and energy policy to cross. Although humans, as a species, are excellent "rapid reactors" (Parkin, 1994), adaptive measures will be taxed to overcome these pressures, and a focus on long-term planning is needed. One important element in a such a planning strategy is the development and use of alternative fuel technologies to diminish petroleum dependence. One particularly promising group of such technologies is the hydrogen fuel cell.

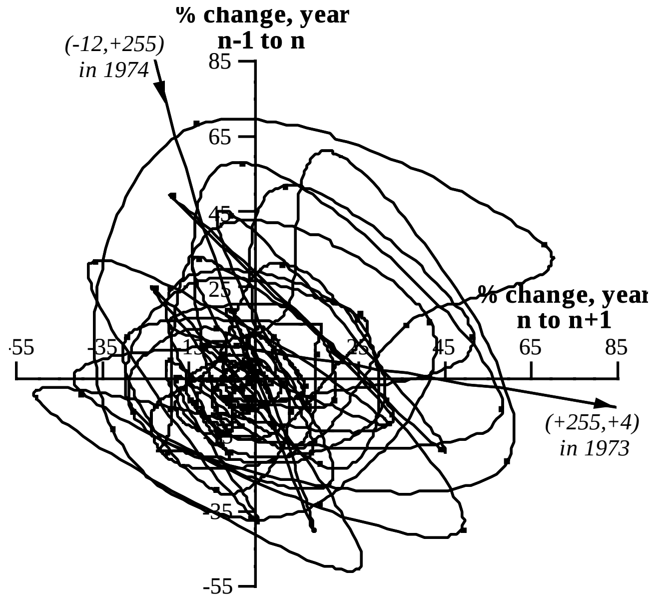
Unfortunately, the uncertainty surrounding the development and commercialization of hydrogen-based transportation systems and their supporting infrastructure is conducive to "serialistic" (Black, 1994) or incremental tendencies that confound effective planning and radical change. Supported by powerful special interests, this incremental *modus operandi* forces us into small adaptations of existing systems and prevents the realization of the benefits of hydrogen-based transport. It tries to cross the chasm of challenges presented by petroleum-based transport in two leaps.

Fortunately, realizing the benefits of hydrogen-based transportation need not depend solely on successful government planning and regulation, nor on incremental adaptation of the status quo. A dramatic transformation now underway in automotive technology—toward ultralight, low-load, hybrid-electric "hypercars™"—may rapidly accelerate the adoption of fuel cells for propulsion by making the automotive platform an attractive environment for these exciting technologies years, perhaps decades, sooner than previously believed.

Interestingly, widespread use of efficient and/or alternatively fueled vehicles could rapidly reduce growth in demand for petroleum products and hence more or less crash the world oil price by creating lasting disequilibrium between supply capacity and demand. Although it is beyond the scope of this exercise to explore such implications for fuel markets, it should be kept in mind that the success of hydrogen and fuel cell technologies should not depend on rising oil prices.

More generally, one could argue that strategic planning must not depend on the predictability of oil price. As shown by H.R. Holt of the U.S. Department of Energy (Figure 1), changes in the real price of crude oil on the world market satisfies every test of statistical randomness. Indeed, it followed a Brownian random-walk trajectory throughout 1881–1993, with a doubling of volatility since 1973 (the offscale excursion on both axes).

Figure 1. The Random Walk Of World Real Crude-Oil Price, 1881–1993



Worldwatch Institute data cited to British Petroleum, BP Statistical Review of World Energy *(London 1993) and electronic database (London 1992); Worldwatch estimates, based on id. and on U.S. DOE'S* Monthly Energy Review *February 1994.*

This paper conceptualizes a hypercar powered by a proton-exchange-membrane fuel cell (PEMFC hypercar). Section II describes the hypercar design philosophy and outlines autobody and component issues, and Section III presents the PEMFC hypercar modeling. The implications of fuel-cell hypercars for the transition to gaseous hydrogen fuel (Section IV) and the rapid commercialization of fuel cells (Section V) are presented. The Appendix provides detailed printouts of the three model scenarios.

By making the car attractive for new technologies, rather than exclusively the other way around, the hypercar concept provides an opportunity to leapfrog past both the undesirable state of dependence on government action or oil prices and the striking challenges facing transportation, to a future of automotive fuel cells powered by hydrogen fuel.

II. HYPERCARS

Concept

During 1991–93, Rocky Mountain Institute (RMI)—a nonprofit resource policy center devoted to resource productivity—explored a set of ideas that, if true, could transform the automotive industry. Working with electric utilities and innovative designers worldwide, RMI Research Director Amory Lovins had been showing for two decades how whole-system redesign of buildings, motors, and many other technical systems that use electricity could often achieve large energy savings more cheaply than small ones.

Rather than treating components in isolation and narrowly optimizing for energy savings in the face of diminishing returns (Figure 2), RMI had discovered that the artful combination of a number of strategies and technologies, many of which would be considered uneconomic, or which would not have been considered at all in the traditional framework, can allow “tunneling through the cost barrier” (Figure 3). RMI suspected that the same might be possible in cars—breaking through the component-oriented mentality that was leading automotive evolution into a cul-de-sac of stagnating efficiency at ever greater complexity and cost.

Figure 2. Incrementalism and Diminishing Returns

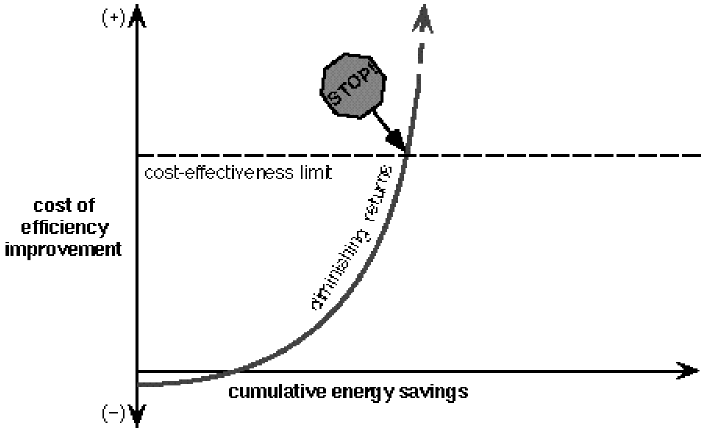
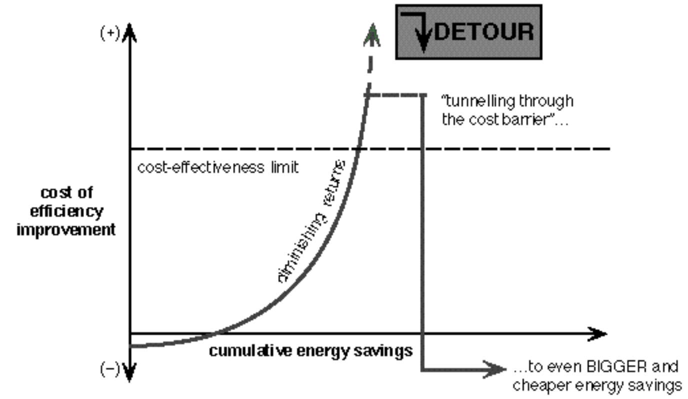


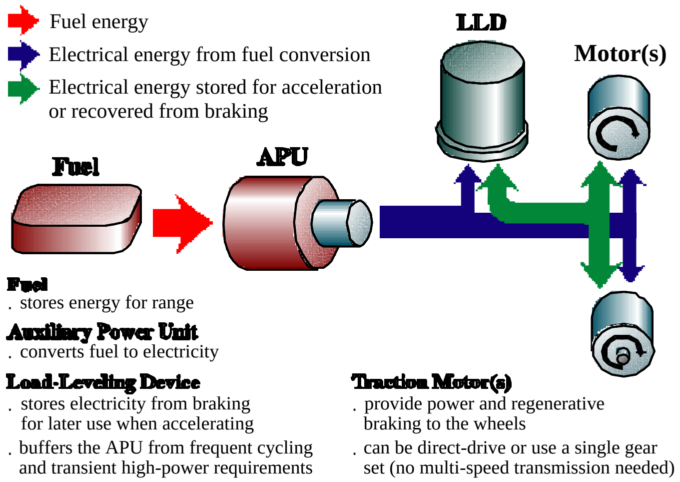
Figure 3. Systems Approach and Leapfrog



Calculations suggested that combining two proven approaches to car design—ultralight and low-load construction, plus “hybrid-electric” propulsion (the century-old concept of powering electric wheel-motors with a small fueled powerplant carried onboard, *e.g.*, Figure 4)—could simultaneously:

- improve modern family cars' fuel efficiency by about three- to sixfold;
- reduce their pollution by one or two orders of magnitude; yet also
- yield comparable or better comfort, refinement, safety, acceleration, and probably affordability.

Figure 4. Energy Flow in a Series Hybrid

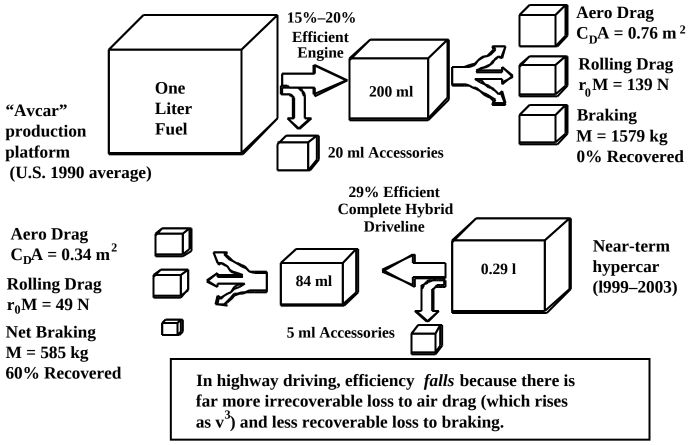


A typical four- to five-passenger "hypercar™," as RMI has dubbed these conceptual vehicles, would need only on the order of two liters of fuel per 100 km—perhaps ultimately only half as much. It could safely, cleanly, and comfortably carry a family 5,000 km across the United States on about 100 liters of virtually any liquid hydrocarbon fuel or its gaseous equivalent.

Figure 5 illustrates the dramatic benefits of load reduction and efficiency improvements. In the top diagram, losses compound as energy flows from the engine to the wheels in a typical vehicle. About 80% of the fuel energy never reaches the wheels: of the roughly one-fifth that does, roughly one-third heats the air through aerodynamic losses, one-third heats the tires and road, and one-third heats the brakes. Moreover, most of this propulsion energy is required to move the vehicle itself. The net result is that an ungratifying 1% of the fuel energy ends up moving the driver.

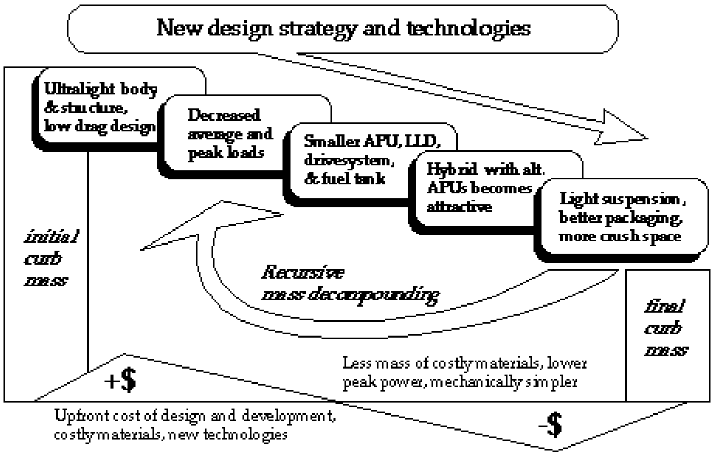
The bottom diagram in Figure 5, however, turns the compounding losses (from engine wheels) into compounding savings (from the wheels upstream to the engine). For each unit of reduction in load at the wheels, or improved efficiency along the way, the associated savings multiply along this chain, reducing by manyfold the amount of fuel that must be used or stored in the first place. Additionally, regenerative braking enables part of the otherwise irrecoverable braking losses to be captured for reuse—although the energy required for braking will also decrease in proportion to gross vehicle mass.

Figure 5. Two Ways to Drive: The End-Use Approach to Reducing Loads



Such exemplary performance would clearly be hard to achieve. It would require highly integrated whole-system engineering, melding dozens of new technologies with meticulous attention to detail. The downsizing, simplification, and elimination necessary to reduce mass, cost, and complexity, and thus enable new options, are hard-won through recursive optimizations at the system level. However, RMI found that meeting this challenge could bring unexpected rewards. Ordinarily, hybrid-electric propulsion tends to make a car heavier, costlier, and more complex. But *prior* reductions both in weight and in air and road drag could turn hybrid drive's "vicious circles" into "virtuous circles," making the hybrid propulsion system lighter, simpler, and cheaper than it would be in a conventional platform. This in turn could trigger further simplification of many automotive systems and components, make most of them much smaller[1], and eliminate some entirely. That would make the car even lighter, further reinforcing the advantages of its hybrid-electric driveline. Repeating this process

Figure 6. Recursive Mass and Cost Decompounding



could make the weight savings snowball, yielding a better car with extremely light weight and probably lower total cost (Figure 6).

RMI found that the engineering principles required were well established; the technologies were demonstrated and some were commercially available. What was needed was an integrated design concept that would reoptimize the car into a new domain of behavior where, paradoxically, seeking to minimize the cost of the car rather than the fuel it consumed would actually lead to its saving even more fuel. Also needed was an equally integrated practical concept of how such a car could be made, sold, and used. By mid-1993, industry presentations, seminars, and technical publications had begun to confirm RMI's early hypotheses. In ever-increasing detail, the 1991 conjecture about the potential for a "leapfrog" in car design seemed to be taking shape.

Commercialization

Starting in mid-1993, RMI adopted an unusual way to speed the commercialization of this apparently promising idea—a way that relies not on governmental mandates or subsidies but on manufacturers' quest for competitive advantage and customers' desire for superior cars. Such a free-market approach appears feasible because hypercars' novel features extend strongly to their method of manufacture.

Making hypercars ultralight, yet also strong for safety, will probably depend on a shift from stamping and welding steel to molding advanced composites made of polymeric materials such as carbon fiber embedded in plastic resin. ("Advanced" means the composite is stronger or stiffer than glass-reinforced composites.) The new materials, and special manufacturing methods adapted from other fields (racecars, aerospace, boatbuilding, etc.) to achieve high volume and low cost, could completely change the way autobodies are made. These new methods could offer the manufacturer a much lower product cycle time, capital investment, assembly effort, and body parts count. The agility, cost, risk, and locality of production would greatly improve. Risks of and barriers to market entry could dramatically diminish.

RMI's commercialization strategy rests on the premise that such potentially decisive competitive advantages will reward early adopters and encourage rapid market entry. Rather than patenting and auctioning the intellectual property, therefore, RMI simply puts most of it into the public domain and seeks to maximize competition in exploiting it. As a result, by the end of 1996, about 25 firms—half current and half intending automakers (from car-parts, aerospace, electronics, and other industries)—were engaged in discussion or collaboration with RMI's Hypercar Center^{SM} on a nonexclusive and compartmentalized basis.

Early success of this commercialization effort holds the promise of achieving the supposedly incompatible car-related public-policy goals for the economy, environment, and national security—simultaneously and robustly. However, this requires discontinuous technological changes in materials, manufacturing, and propulsion systems; re-integration of the automotive design process; and other major cultural changes in automaking and in wider engineering and commercial practice. It is not yet clear whether automakers can achieve these changes, or whether they might instead be displaced by new market entrants who have none of the automakers' vast physical and human capital trapped in established manufacturing modes, such as stamping and welding steel. Commercial developments remain extremely fluid, and which firms, or even which kinds of firms, will win the race cannot yet be anticipated.

Autobody Design Options

The body of a car currently accounts for one-fourth of its total curb (*i.e.*, empty) weight; is its largest single system; provides its structural integrity, safety, and comfort; and largely determines its look, feel, and market attraction. For an ultralight-hybrid hypercar, the body becomes even more important, because its structure and materials are the keys to making the whole car ultralight and low-drag.

The feasibility of hypercars as practical and profitable products therefore depends critically on making the body extremely light without compromising its basic requirements. It must also be cost-competitive. A hypercar might cost less than a standard car even if its body cost more, because the body would be so light that the rest of the car could become cheaper, but the case is more compelling if the ultralight body itself also costs less to make than the standard steel unibody. Several different but convergent kinds of designs appear able to achieve this. Among them, true "monocoques" (whose shell is the structure—much like the light, thin, but hard-to-break shell of a lobster) appear better able than spaceframe- or unibody-based alternatives to achieve maximum strength with the least weight.

Though certain innovative approaches with light metals, or even with advanced steel structures, may offer significant palliatives, it is highly advantageous to "leapfrog" autobody design directly to new ways of mass-producing the body-in-white (BIW) from advanced composites.

The benefits of this major shift in materials, design, and manufacturing could include:

- greatly reduced fuel consumption and emissions;
- unchanged or improved crashworthiness (partly because advanced-composite structures can absorb five times as much crash energy per kg as steel);
- more quiet and refined operation (because composites, especially foam cores, can suppress noise, vibration, and

harshness better than metal bodies);
- increased stylistic flexibility and improved fit, finish, and aesthetics (such as the virtually invisible seams made possible by composites' tight molding tolerances);
- freedom from rust, greater resistance to minor dents and scratches, and generally greater durability, but at least comparable and perhaps better recyclability;
- an order of magnitude fewer body parts;
- safer, less polluting, and less wasteful methods of production; and
- more agile and less financially risky production and marketing with lower fixed costs, comparable or possibly lower total costs, small breakeven sales volumes, diversified model portfolios, rapid product cycles, and ability to respond quickly to changing markets.

Achieving these results reliably requires a challenging short-term reliance on highly integrated and often unfamiliar techniques, materials, and optimization methods. However, the initial costs would be such a small fraction of the roughly $1 billion required to tool up a new steel-car model (often nearer $4–6 billion for that model's total development investment) that automakers, whether large and risk-averse or smaller and perhaps more receptive to taking risks to get ahead, may find ample motivation. Those who act swiftly could be rewarded with competitive advantages as decisive as those Henry Ford achieved with his 1908 Model T.

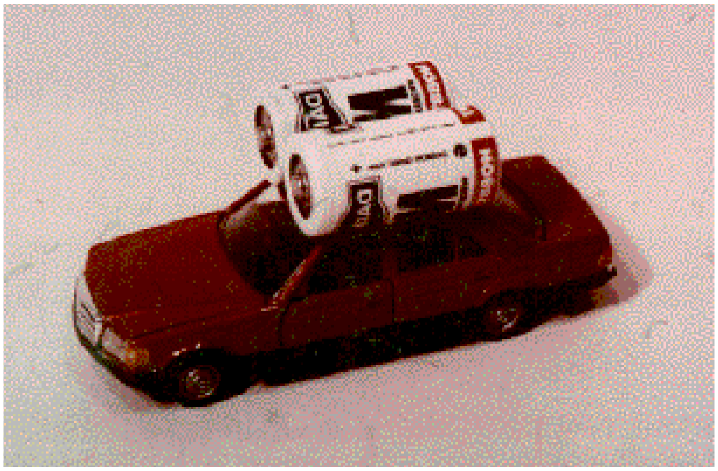
Components

Components other than the body-in-white would account for about 70–80% of the hypercar's curb weight. About 40% of the total curb weight would be the miscellaneous non-propulsion systems that are normally considered minor in today's cars. Many of these require special design attention to reduce mass and accessory loads, which could offset the hypercar's great propulsive efficiency if not reduced by at least severalfold, as today's best technologies appear to permit.

Many hypercar components would be similar to today's, but much smaller and lighter. The main differences would probably include:

- Some components, such as power steering and power brake booster, become unnecessary with ultralight construction, while others, such as the starter, alternator, axles, differentials, multispeed transmission, clutch, driveshaft, and universal joints, could be displaced by the hybrid drivesystem.
- Except in some early models that might use a small internal-combustion engine for convenience, the powerplant would probably range from modestly different (Stirling or gas-turbine) to profoundly different with no moving parts (fuel cell or thermophotovoltaic).
- Rather than hauling a half-tonne of batteries for driving range (Figure 7), buffer storage might entail a high-specific-power (>800 W/kg) nickel-metal-hydride or wound-foil lead-acid battery roughly three times heavier than today's cars' ordinary 14-kg lead-acid starting battery, but lasting about as long as the car. Later, carbon-fiber superflywheels, ultracapacitors, thin-film lithium batteries, or some combination of these technologies could be used.

Figure 7. The Battery Car



Courtesy of the Technical University of Darmstadt.

- Power electronics could be far smaller in mass, size, and cost than for today's battery-electric cars, because the platform would be severalfold lighter (not requiring a large battery bank).
- Each component, subsystem, and system would require and receive rigorous and holistic design. Many subtle energy losses or mass accretions now considered negligible would become important and would be minimized.

Technologies identified as particularly attractive, though not essential, for a successful hypercar include advanced switched-reluctance motor/generators and power electronics, Stirling Thermal Motors' external-combustion engine (now completing several years' reliability testing), proton-exchange-membrane fuel cells, and a wide range of specific technologies related to suspension and steering, brakes, wheels, tires, glazings, interior climate control, seats, safety equipment, lights, electricals, instruments, and controls. More important than any of these will be a highly integrative whole-platform design process that fully exploits the potential of the hypercar's enlarged "design space."

III. FUEL-CELL HYPERCARS

Using the design philosophy described in the previous section, RMI has now undertaken the task of conceptualizing and modeling a hypercar powered by a proton-exchange-membrane fuel cell.

Modeling

To explore hypercar-optimization issues more quantitatively, RMI developed parametric spreadsheets[2] for use in combination with SIMPLEV—a second-by-second, component-matrix-based simulation tool (Cole 1993).

The spreadsheet model consists of a detailed mass budget for the vehicle as well as tools for estimating various aspects of vehicle performance and fuel economy. Using these heuristic tools to derive inputs for SIMPLEV, the conceptual vehicle was run through the U.S. Federal Urban Driving Schedule (FUDS) and the U.S. Federal Highway Driving Cycle. To represent more realistic driving conditions, the conceptual vehicle was also run through versions of those cycles with all second-by-second velocities multiplied by 1.3, as well as through the US06 Driving Cycle. (The "intensified" driving cycles, which simultaneously correct power, energy-storage, and emissions parameters, yield somewhat worse fuel economies than the correction factors applied to fuel-economy results by the U.S. Environmental Protection Agency.)

The adaptation of RMI spreadsheet models, and the outputs of SIMPLEV for three fuel-cell hypercar scenarios, are included in the Appendix. The three scenarios modeled were: a "base-case" scenario optimized in traditional hypercar fashion with a relatively high-power (36 kW) load-leveling device (LLD), a "min-LLD" scenario using considerably less LLD power capacity (12 kW), and a "no-LLD" scenario where the fuel-cell powerplant was sized to meet all performance criteria without the assistance of a high-power electrical storage device. The latter two scenarios were undertaken to try to take advantage of the fuel cell's excellent load-following capabilities due to its high efficiency at partial loads (see Figure 8).

To assure the broad salability of any conceptual PEMFC hypercar modeled, demanding performance criteria were met in each of the three scenarios.

Design Criteria

Industry design criteria for efficient vehicles have tended to focus on limiting compromises in performance rather than on *improving* it. Marketability, however, probably dictates that new vehicles must be not only equivalent to those they displace but in some way *more* attractive to consumers. RMI's analyses suggest that hypercars would yield generally improved acceleration, handling, braking, safety, and durability. Since fuel economy and emissions are low on the list of criteria for most consumers today, and may be lower in the future (based on increased popularity of sport-utility vehicles and minivans), efficient vehicles must be better in other respects if they are to gain the large market share required to provide significant societal benefits. The following criteria (based in part on similar criteria developed by the U.S. Partnership for a New Generation of Vehicles, or PNGV) appear essential for the U.S. market, and were thus assumed for this analysis (all improvements are relative to current touring-class production sedans):

- acceleration from 0 to 100 km/h in 8.5 s at "test mass" (with two 68-kg occupants) or in 12 s at "gross mass" (six 68-kg occupants plus 91 kg luggage);
- gradability sufficient to maintain 105 km/h on a 6.5% grade at test mass or 90 km/h at gross mass for 20 minutes;
- improved handling, maneuverability, tire adhesion, antilock braking, and traction control;
- improved crashworthiness, interior safety features, and ease, speed, and safety of post-crash extrication;
- combined urban/highway range of 640 km;
- at least equivalent ride and handling;
- improved noise, vibration, and harshness (NVH) characteristics;
- carrying capacity for the gross-mass load and occupants with equivalent comfort and cargo space;
- useful life of 320,000 km, maintenance of original performance specifications for at least 160,000 km, improved service intervals, and comparable reliability and refueling time; and
- equivalent or improved customer features, such as climate control and entertainment systems, and total real cost of ownership.

In particular, it is important to note that the acceleration criteria set out here are significantly more demanding than the PNGV targets. (For example, the PNGV target for 0–96.6 km/h (60 mi/h) at test mass is 12 s.)

Key Modeling Assumptions

Vehicle Parameters

The vehicles modeled all assume the following bulk parameters:

Coefficient of aerodynamic drag (C_D)	0.2
Frontal area (A)	2.0 m^2
C_DA	0.4 m^2
Coefficient of rolling resistance, with toe-in	0.0062
Maximum vehicle speed (regulated)	129 km/h

Key Component Assumptions

Based on previous RMI benchmarking to technologies that appear ready for high-volume production by ~2002-2004:

Body-In-White (BIW):

- 153 kg, based on a major automaker's validated all-aluminum unibody BIW (with closures). Although carbon-fiber-dominated advanced-composite monocoque BIWs should be able to do better, this is a remarkable accomplishment for aluminum and should have no problem supporting the gross loadings of any of the three scenarios. Previous modeling assumed a 150-kg advanced-composite BIW (with closures).

Fuel Cell and Related Systems:

- 3.15 lb/gross kW bare stack (Ballard) + 1 lb/gross kW balance-of-system (~2004 estimate by James 1997) + 1 lb/gross kW radiator, coolant, deionizing fluid, pumps, filters, etc. (*id.*) = 2.34 kg/gross kW.
- 8-kg latent heat (phase-change) battery + 5 kg of insulation for fuel-cell freeze protection.

The time allowed for the fuel cell to ramp up to full power (based on estimates for an appropriate expander/compressor @ 3 atm) was set at 1.55 seconds for all scenarios. Please see the discussion for more information.

Fuel Systems:

- 4.65 kg of hydrogen in a 34.4-kg, 345-bar (5,000-psia), filament-wound T-1000 carbon-fiber[3] tank lined with metalized polyester film[4] (Thomas 1997).
- 2 kg of fuel delivery, sensors, etc.

Motor:

- Unique Mobility SR218H permanent magnet motors, scaled from 42 kg to fulfill starting torque requirements.

Load-Leveling Device (LLD):

Three scenarios were modeled with varying sizes of LLD, based on available modules of the Bolder Technologies thin-foil lead-acid battery. In the "base-case" scenario, the fuel cell is sized to meet the gradability target (90 km/h) at gross mass on a 6.5% grade, and the LLD is sized for acceleration and acceptable capacity for multiple passes on a grade at gross mass (see the discussion for more information). In the "min-LLD" scenario, the fuel cell is sized to meet passing requirements on a grade at gross mass, and a small module of the Bolder Technologies battery is used to meet acceleration requirements and to allow for regenerative braking. In the "no-LLD" scenario, the fuel cell is sized to meet all acceleration and gradability requirements.

RESULTS

The three PEMFC hypercar scenarios were designed and optimized using RMI spreadsheets (Table 1), and were modeled in SIMPLEV[5] over several driving cycles (Table 2).

Table 1. Performance Results

Scenario	Curb Mass (kg)	0-100km/h @ test mass (M_{test})	0-100km/h @ gross mass (M_{gross})	Speed on 6.5% grade @ M_{gross}
Base-case	712	7.2 s	10.2 s	90 km/h
Min-LLD	772	7.9 s	11.0 s	140 km/h
No-LLD	790	8.2 s	11.4 s	155 km/h

All times were calculated with 500W of accessories turned on.

Table 2. SIMPLEV Fuel-Efficiency Results

Scenario	Curb Mass (kg)	Intensified FUDS mpg_{equiv} (km/kg)	Intensified 55/45 FUDS/Highway mpg_{equiv} (km/kg)	US06 mpg_{equiv} (km/kg)
Base-case	712	124 (205)	120 (199)	100 (166)
Min-LLD	772	117 (194)	115 (190)	96 (159)
No-LLD	790	102 (169)	109 (180)	91 (151)

The LLD increments modeled, based on available modules, were:

- Base-case: 42-kg, 36-kW Bolder Technologies thin-foil lead-acid.
- Min-LLD: 14-kg, 12-kW Bolder Technologies thin-foil lead-acid.

Control Strategy

The following methods were used to represent appropriate vehicle control strategy:

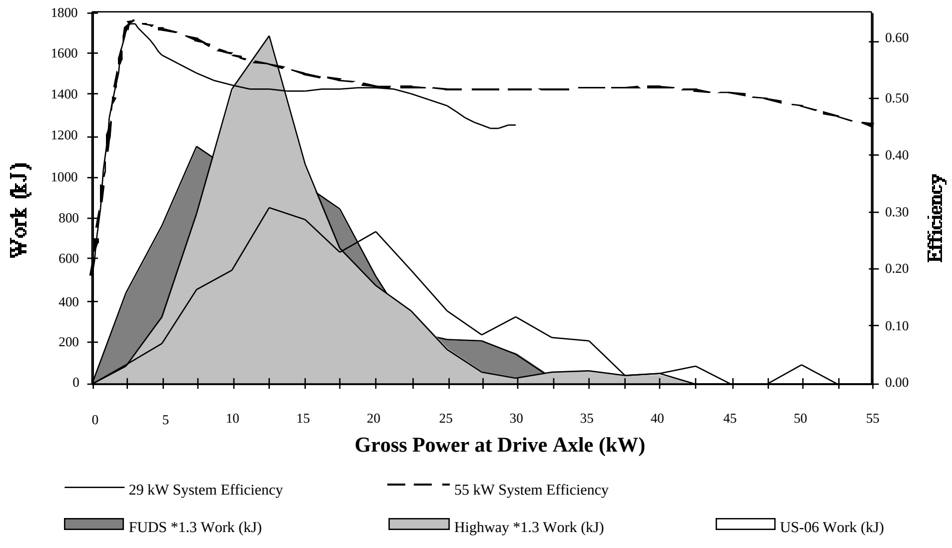
- The minimum operating power fraction for the fuel cell was set at 0.04, yielding a minimum operating power of 1.2 kW, 2.2 kW, and 2.6 kW for the base-case, min-LLD, and no-LLD scenarios, respectively.
- In the base-case and min-LLD, the lead-acid battery was allowed to move between 50% and 65% state of charge (SOC).
- DC to DC conversion was accounted for in the base-case and min-LLD scenarios by doubling the internal resistance of the lead-acid battery.

Discussion

Fuel Cell Efficiency and Driving Work: A Good Match

To match zones of highest efficiency to typical use patterns, designers of powerplants, load-leveling devices, and power electronics need to know the relative distribution of *cumulative* energy throughput at various power levels over representative driving cycles. A simple graph showing cumulative energy throughput at various power levels for a base-case PEMFC hypercar over the duration of a complete intensified FUDS cycle is shown in Figure 8. On top of that graph is drawn a representative efficiency-vs.-power curve for a PEMFC (scaled from a DTI representation, Thomas 1997). The relative conformity of the high-efficiency zones of this curve to the areas of largest cumulative energy throughput suggest an elegant match between fuel-cell efficiency and typical driving conditions. This match is significantly superior to that achievable by combustion engines, which generally increase steadily from low efficiency at low power to higher efficiency (although still low relative to the fuel-cell) at full power.

Figure 8. Fuel-Cell Efficiency and Driving-Cycle Work



This match suggests that, even in a hybrid-electric configuration *with* a load-leveling device, the fuel cell has tremendous potential to follow most driving loads while maintaining high efficiencies. To the extent that the region of high cumulative energy throughput is significantly higher than (shifted to the right of) the power fraction at which the fuel cell operates at highest efficiency, however, the load-leveling device will still play an important role in the overall control strategy. This and other factors that determine the sizing of the LLD are discussed in the next subsection.

Sizing the Load-Leveling Device

The high part-load efficiencies of a fuel cell (Figure 8) argue that a large fuel cell should be used, and that only minimal load-leveling is required. Although the fuel cell has tremendous load-following capabilities, other important consequences of downsizing the high-specific-power load-leveling device are highlighted by a comparison of the three scenarios modeled. Among these consequences are:

- mass compounding (712 kg vs. 772 or 790 kg);
- overall fuel economy reduction (120 mpgequiv vs. 115

or 109 mpgequiv);

- poorer 0–100 km/h acceleration (7.2 seconds vs. 7.9 or 8.2 seconds).

Because a larger fuel-cell APU is used, however, the minimum-LLD and no-LLD scenarios have much better gradability (90 km/h on a 6.5% grade at gross mass vs. 140 or 155 km/h), although all three meet the PNGV design targets. Also, the no-LLD scenario actually shows *increased* fuel economy for highway driving, The is because the cruising loads at highway speeds are well suited to a large APU, and because fewer hard transients and opportunities for regenerative braking exist under these conditions.

Number of Passes on a Grade

Built into the control strategy for the base-case scenario is the very gradual reduction in power available to the driver as LLD charge is depleted when passing repeatedly on a hill at gross mass (see Moore 1996a for more detail). On the performance spreadsheet for this scenario, a simple calculation has been included to indicate the number of 60–100 km/h passes (currently five) that are available to the driver on a 6.5% grade at gross mass, using only 40% of the LLD's charge. This does *not* include any contribution from regenerative braking or from the fuel cell, which is sized to maintain a 90 km/h speed indefinitely at gross mass on a 6.5% grade. Estimates indicate that the fuel cell would typically add at least one pass per eight LLD passes. A greater contribution would result from LLD charging if the vehicle spent any significant time below 90 km/h.

Performance Sensitivity and Fuel-Cell Ramp-Up Time

A somewhat arbitrary total time of 1.55 seconds was chosen to allow the fuel cell to ramp up to full power, based on estimates of the part-load behavior of an appropriate three-atmosphere compressor. To test the sensitivity of vehicle performance to this assumption, a base-case scenario PEMFC hypercar was allowed 3.8 seconds to ramp up to full power (based on estimates including some allowance for a cold start). Given this assumption, the model predicted a 0–100 km/h time of 7.9 seconds at test mass, rather than the 7.2 seconds presented in the results subsection. Although this comparison is not rigorous, it can be seen that even a conservative assumption for fuel-cell ramp-up would still allow the performance target of 8.5 seconds to be met, by a considerable margin, in the base-case scenario.

IV. FUEL SHIFTING

> "Hydrogen is a logical choice because it doesn't pollute. But hydrogen tanks are huge and heavy."
>
> —*USA Today,* 24 February 1997

A shift to hydrogen fuel could greatly reduce both the air pollution and the climatic effects of cars, but there is a widespread misconception that hydrogen storage must be prohibitively bulky. Except in special fleet-vehicle cases, gaseous fueling is seldom seen as attractive today because:

- the cars themselves are so inefficient that large, heavy, and costly tanks are needed to carry enough fuel for substantial range;
- their more frequent refueling may require more ubiquitous and hence more costly refueling infrastructure;
- they would consume significant amounts of a costlier fuel; and
- the fuel-cell stack (the ideal way to convert energy from gases to electricity) required to propel such heavy cars would itself be excessively heavy, bulky, and expensive.

However, in a 1994 conceptual study for Argonne National Laboratory, Directed Technologies, Inc. (DTI) concluded that a Ford Taurus converted into a proton-exchange-membrane fuel cell (PEMFC) hybrid, and fueled with a strong, safe, compressed-hydrogen tank weighing less than a filled gasoline tank, could provide range comparable to that of the original gasoline-fueled Taurus if a severalfold larger tank could be accommodated (James *et al.* 1994). DTI also found that if the hydrogen were made by splitting water with cheap offpeak retail electricity in mass-produced electrolyzers, the hybrid's fuel would be cost-competitive on a per-kilometer basis with American taxed gasoline (Thomas and Kuhn 1995).

These impressive findings result from the severalfold higher efficiency of converting gaseous hydrogen rather than gasoline into tractive energy: the electricity used to make the hydrogen is a costlier energy carrier[6], but hydrogen's efficient use, via the hydrogen-fuel-cell cycle, more than compensates. (Specifically, the fuel cell is nearly twice as efficient as the *peak* efficiency of an ordinary spark-ignition, gasoline-fueled, internal-combustion engine, and over three times as efficient as the *average* efficiency of such an engine in a non-hybrid car, integrating over a typical driving cycle.) DTI's conceptual Taurus conversion, however, did not assume the significant improvements in platform physics posited by the hypercar concept. [7]

Hypercars Make Compressed Gaseous Fuels Practical

According to preliminary modeling, a PEMFC hypercar would convert hydrogen into traction about four to six times more efficiently than today's cars convert gasoline into traction. Hypercars should thus need so little fuel that a small, light, cheap tank of compressed hydrogen gas or natural gas could take them a very long distance—thereby largely or wholly offsetting hydrogen gas's low energy content per liter. Moreover, PEMFCs have net peak efficiencies of over 60%

when fueled with hydrogen, and achieve high efficiency over a wide range of partial loads well matched to common driving conditions. Requiring so little fuel for a given range, hypercars could thus afford to use relatively costly fuel, such as hydrogen reformed from natural gas or electrolyzed from water. (For example, if the car uses only a sixth as much fuel, the fuel will cost the same per *kilometer* even if it costs six times as much per *megajoule*.) Hypercars could achieve these results without compromising performance. This does an end-run around the fuel-price-elasticity debate, and makes rapid market success much more probable.

Additionally, hypercars would make fuel cells—the ideal way to use hydrogen—a far more robust vehicular powerplant option by reducing the kilowatt output capacity, physical size, mass, and cost of the fuel cells *required to run* the car, thus providing generous safety margins and multiple technological backstops to fuel-cell development (see Section V); more good eggs in the compressed-methane-or-hydrogen basket.

In short, hypercars could:

- make hydrogen's success as the main fuel for road vehicles significantly less dependent on decreasing fuel-cell cost, size, and weight;
- accommodate a more gradual phase-in of a hydrogen refueling infrastructure;
- ensure the competitiveness of gaseous automotive fuels even if fuel cells fail to meet their design goals and another form of APU must be substituted (in other words, they diversify the APU portfolio suitable for gaseous fuels);
- rely for their success on consumers' demand for superior

Table 3. Illustrative Tankage for Compressed-Hydrogen Fuel-Cell Hypercars

		Gaseous H_2	**Gasoline**
tank		filament-wound T-1000 C, aluminized polyester film liner, 2.25 safety factor (USDOT standard)	rough estimates of ordinary automotive tankage
design pressure		345 bar (5,000 psia)	1.01 bar (14.7 psia)
fuel energy–LHV		558 MJ	558 MJ
fuel mass		4.65 kg	12.6 kg
filled tank mass		39.0 kg	~16 kg
tank volume		~240 L (~63 gal)	~19 L (~4.9 gal)
fuel/(filled tank) mass ratio		0.12	0.76
hypercar's range @ 199 km/kg, based on the base-case spreadsheet model		~925 km (575 mi) [99.0%]*	—
driving range of that 17.9 L of gasoline @ 8.84 L/100 km (PNGV benchmark for midsize sedan)		—	203 km (126 mi) [100%]*
	L of gasoline to get same range as H_2	—	86 L (23 gal) [95%]*
	kg of filled gasoline tank to get same range as H_2	—	~75 kg 60 kg fuel
H_2/gasoline ratio of filled tanks for the same driving range	**mass**	**0.5**	—
	volume	**~2.5**	—
	fuel MJ	0.2	—

*[x%] = Usable fuel percentage. For example, James *et al.* (1994) suggest that only 94.7% of 72 liters (18 out of 19 gallons) of gasoline is usable in a conventional Taurus-class vehicle, mainly because of the need to accommodate the liquid's tilt and slosh in a moving vehicle while keeping the liquid-fuel pump fed. This correction is highly dependent on the geometry of the gasoline tank. In contrast, compressed-hydrogen tanks described above can discharge down to the minimum pressure required by the fuel cell plus in-line pressure drop (assumed here to total roughly 50 psia), and hence will have a usable fraction over 99%.

performance and features, not on cleanliness or efficiency, and on automakers' pursuit of competitive advantage, not on government mandates like ZEV or CAFE; and
- by these means make achievement of a hydrogen road transport sector far more likely.

Depending on how sanguine one is about the chances of hydrogen becoming a cheap, convenient, and widely available fuel, this complementary approach from the other direction—making the car ideal for hydrogen, not just the other way around—could be considered a selling tool, a vital foundation, or an insurance policy. Either way, it is a sound investment, adding yet another motivation to the commercialization of hypercars.

Onboard Storage: Hydrogen's Achilles' Heel?

An important feature of pressurized-hydrogen fuel-cell hypercars worth highlighting is their modest tankage requirements. Although DTI claims that volumes up to five times greater than the original gasoline tank could be accommodated in a vehicle with careful packaging (James *et al.* 1994), they recognize that tankage much more comparable in size to a gasoline tank is usually required. To illustrate the onboard storage requirements for a PEMFC hypercar, consider such a car fueled with 4.65 kg of hydrogen stored onboard in a carbon-fiber tank like the one described in the component assumptions in Section III. Integrated into a vehicle, such a tank design, suggested by Fred Mitlitsky of Lawrence Livermore National Laboratories (LLNL) and described by DTI, could provide greater safety than conventionally packaged gasoline.[8]

Table 3 illustrates that, if the tank described above were put into the base-case PEMFC hypercar, it would only be about 2.5 times larger—and about 50% *lighter*[9]—than the gasoline tank required to give a conventional vehicle the same driving range (about 925 km).

Even using the presently required U.S. tank safety factor (ratio of rupture to design pressure) of 2.25, these results are impressive. But though the reasons for regulatory conservatism are understandable, that safety factor appears to reflect traditional understanding of metal tanks prone to fatigue, embrittlement, corrosion, and considerable manufacturing variability. Greater experience may well persuade the safety authorities that the advanced-composite tanks analyzed here lack these drawbacks, and that a safety factor of around 2.0 is very reasonable with careful quality assurance (including non-destructive testing) in materials and mass production, perhaps supplemented by embedded damage or stress sensors.

The exceptional driving range offered by a hypercar with just 4.65 kg of hydrogen is an attractive feature, particularly while the hydrogen refueling infrastructure is young. But it is important to note that the extra onboard storage capacity could be partly traded away for better packaging, reduced pressurization levels, or savings in tank and vehicle mass. This design-space "breathing room,"—a result of first optimizing the vehicle loads and efficiency—is also an important aspect of determining vehicular requirements for fuel cells. This flexibility makes the success of PEMFC hypercars more likely.

V. ACCELERATED COMMERCIALIZATION OF FUEL CELLS

PEMFCs have recently achieved important breakthroughs. Ballard Power Systems met performance standards in 1995 that U.S. Department of Energy goals did not expect to be met until five years later. International Fuel Cells continues its promising development of self-humidifying, near-ambient-operating-pressure stacks that could be glued rather than bolted together and use blow-molded polymer manifolds. PEMFCs are widely agreed to be producible for a few hundred dollars per kW. However, three relatively recent evaluations—by GM's Allison division (Allison 1993), A.D. Little, Inc. (Bentley 1995), and Directed Technologies, Inc. (Thomas and Kuhn 1995; James *et al.* 1994; Kuhn 1995)—reflect a growing consensus that hydrogen/air PEMFCs at high production volumes could probably achieve manufacturing costs below $50 per gross kW. This is plausible, because the cells are solid-state, made of standard materials, need no more platinum-group catalyst per car than an ordinary catalytic converter, and might even be made by joining together specially premolded roll-to-roll polymer products containing the catalytic membrane, gas-flow channels, electrodes, etc.

Currently, however, PEMFCs are essentially handmade prototypes, and they cost several thousand dollars per kW. Significant uncertainly will continue to surround the rate and magnitude of cost reductions as PEMFCs mature with continued development, and as production volumes rise in response to emerging stationary and/or transit-vehicle markets. Many believe that we are no closer to answering the question, "When can I buy a fuel-cell car?" than we were a decade ago. Hypercars, however, might help change this.

The foregoing logic of using hypercars to hasten the commercialization of hydrogen fuel becomes especially interesting when applied to PEMFCs. Hypercars' distinctive advantage in accelerating the mass-production of PEMFCs comes from their needing significantly fewer gross kW of onboard power generating capacity, because their road loads are two- to three-fold lower and most of their peak power requirements are met by the load-leveling device, not the onboard generator. For example, the base-case model of a five- to six-passenger PEMFC hypercar, which meets PNGV goals with considerably better acceleration, would need only ~29 net kW of peak

Table 4. Illustrative Fuel-Cell Requirements: Taurus-Conversion vs. Hypercar

	Taurus conversion (James et al. 1994)		PEMFC hypercar (Appendix)		% change Taurus conversion to hypercar	
	FC + LLD	Pure FC	FC + LLD "Base-case"	Pure FC "No-LLD"	FC + LLD	Pure FC
Total net kW	85 kW		65 kW		-24%	
LLD kW	45 kW	-	36 kW	-	-20%	-
LLD competitive cost threshold	$18/peak kW	-	$22/peak kW*	-	+22%	-
PEMFC net kW	40 kW	85 kW	29 kW	65 kW	-27%	-24%
FC competitive cost threshold	**$37/net kW**	**$27/net kW****	**$51/net kW***	**$35/net kW****	**+38%**	**+30%**
FC + LLD cost	$2,290	≈$2,290	≈$2,290	≈$2,290	set equal to Taurus FC + LLD	
0–100 km/h time	10 s		7.2 s***	8.2 s***	(to illustrate conservatism)	

*Calculated, based on percentage change from DTI numbers.
**Calculated, based on FC + LLD cost of the Taurus-class hybrid.
***With 500W of accessories turned on.

continuous DC power rating from its APU, compared with 104 kW[10] of mechanical shaftpower from the Taurus's internal-combustion engine. A better-optimized four- to five-passenger hypercar would need even less. Hence, after due correction for driveline efficiency and LLD cost, hypercars should be much less sensitive to APU *cost per kW*. This unique feature could propel PEMFCs rapidly into high-volume production, and hence even lower cost, by making it economically possible to use the fuel cells *at a much earlier stage of their development*—before they become nearly as light, small, and cheap per kilowatt as they will later.

Table 4 is a conservative comparison of the kW requirements for various platforms and illustrates the improved cost-competitiveness of fuel cells used in lower-load cars. According to DTI's 1994 report, a standard Taurus-class car requires about 85 net kW of fuel cells for performance comparable to its ICE counterpart. When configured with a 45 kW load-leveling device, only 40 net kW would be required, and those fuel cells could compete in capital cost with the Taurus's internal-combustion-engine mechanical driveline if they cost about $37/kW. But a Taurus-class PEMFC hypercar, needing only 29 net kW of fuel cells, would therefore be competitive using PEMFCs that cost 38% more.

It is important to note that Table 4 is only a rough, side-by-side comparison of one or two components, and it does not fully capture the economic incentive for using fuel cells in low-load cars. A more rigorous analysis would no doubt uncover increasing benefits as the vehicle were optimized at a system level. Depending on vehicle priorities, the additional degrees of freedom, or design-space breathing room, earned by up-front load reduction and efficiency improvement could be "cashed in" for an improved commercialization scenario for the automotive fuel cell. As previously mentioned, reducing the PEMFC hypercar's range to that of a conventional car would result in even more modest tankage requirements and the associated savings in mass, cost, and packaging could be factored into the optimization. More directly, reducing the acceleration capabilities of the conceptual hypercar from a touring-class vehicle to that of a peppy standard-class vehicle could significantly advance the date of automotive adoption of fuel cells (within marketing constraints) by further lowering the price hurdle that this promising young contender must overcome.

The difficulty of accommodating new technologies in conventional cars is presumably why, despite otherwise demanding requirements, the PNGV target for 0–60 mi/h is a doggish 12 seconds. One might also argue that PEMFCs should be introduced first in smaller, lighter, four- to five-passenger car models in order to build PEMFC production volumes and cut costs. Our modeling of the PNGV five- to six-passenger platform thus understates hypercars' full potential to accelerate fuel-cell commercialization.

Cheap PEM Fuel Cells Could Widely Displace Thermal Power Stations

Even with comparatively greater price tolerance, hypercars still require fuel cells that cost substantially less than they do today. However, important opportunities exist in many building applications that can build fuel-cell volumes and cut cost.

Fueled with reformed natural gas, PEMFCs should be able to undercut the short-run marginal cost of generating power from even the most efficient thermal power stations. For example, the net electrical output efficiency of a stationary PEMFC using reformed methane is often quoted at about 40% (LHV) with neither heat recovery from the stack to the reformer nor pressure recovery from the stack's hydrogen input and stack output to the air compressor. With both, the best technology is now typically closer to 50%. Natural gas at \$3.70/GJ or \$4/1000 ft^3 (the average U.S. price to CNG fleet-vehicle refueling stations in 1992–93) would thus produce electricity at 3.0¢/kWh: 2.7¢/kWh for the fuel plus 0.3¢/kWh for the cost of a fuel cell at ~\$200/kW.[11] Note that this is the delivered electricity price, not busbar: it avoids all grid costs and losses, making three-cent power easily competitive with almost every utility's short-run marginal cost, even from the newest ~60%-efficient, but centrally located, combined-cycle gas turbines. In effect, the PEMFC is about as efficient as those turbines, but far smaller and more modular, easier to mass-produce, and probably cheaper per delivered kW even at modest production volumes.

However, this comparison neglects one of the fuel cell's most valuable benefits: it continuously produces not only electricity but also waste heat with a useful temperature of about 80°C, ideal for heating and cooling buildings or for heating domestic water. Such waste heat is valuable, because it can displace heat otherwise produced from furnaces or boilers that have their own costs and losses, both valuable to avoid. Each kWh (3.6 MJ) of fuel used by the PEMFC will yield about 1.8 MJ of electricity plus up to 1.8 MJ of waste heat[12], which when timely (needed approximately when produced) can displace up to 2.6 MJ of fuel normally used by a typical ~70%-efficient commercial boiler. The avoided boiler fuel is thus worth a fraction of the fuel cell's fuel cost (about 2.6/3.6), multiplied by the duty factor of the local heat requirements. For a typical commercial building requiring substantial heating or cooling at virtually all times of the day and year, this waste-heat credit (plus an estimated 3% allowance for displacing the capital and maintenance costs of the boiler) would offset three-fourths of the fuel cell's natural-gas costs, reducing the effective net cost of the electricity to only 1.0¢/kWh. Fuel, operation, maintenance, and major-repair costs of a typical central power plant is about 2.5¢/kWh. And, delivering the average kilowatt-hour costs 2.3¢/kWh.

To be sure, the actual site-specific comparison is far more complex, because persistent temporal imbalances—the less efficient the buildings, probably the greater the imbalances—are likely between the supply of and the demand for both heat and electricity. But real-time electricity pricing, the relative ease of storing heat, and the prospect that cheap superflywheel or ultracapacitor electrical storage will enter the market in the late 1990s (also stimulated by the vehicular market) all suggest that these details will not materially change the conclusion: cheap PEMFCs could economically and practically displace any thermal power station in circumstances that occur widely—wherever there is natural gas and a moderately frequent market (even as small as kilowatt-scale) for the waste heat.

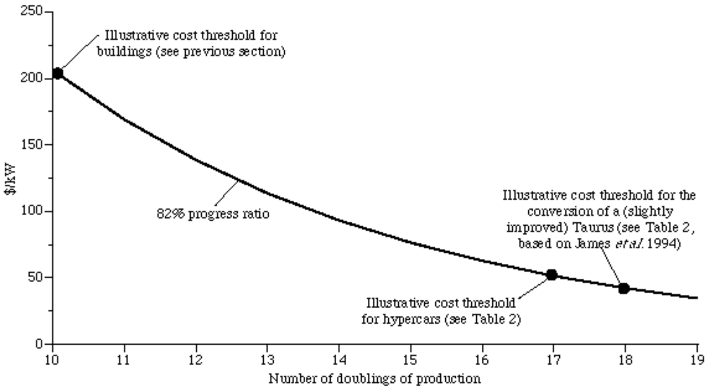
Buildings use two-thirds of U.S. electricity. In principle, such a formidable competitor could put a significant portion of thermal power plants out of business. But the competitive prospect does not stop with buildings. The current U.S. private fleet of some 150 million cars, excluding other motor vehicles, and averaging 20 continuously rated kW of onboard fuel-cell APU capacity per vehicle, would represent a generating capacity about five times that of all U.S. electric utilities. The fuel cells could be run silently, very cleanly, and at low marginal capital cost (since they are already paid for and promise to be durable) when plugged into both the electric and the natural-gas grids, assuming a simple reformer to produce hydrogen at, or sufficiently near, the plug-in site. The average American car is parked ~96% of the time, usually in habitual sites such as the home or workplace. Although the electric-and-gas connection would have a capital and metering cost, it would typically be in sites already served, or nearly served, by both grids, and the cost of the electric hookup would probably be less than the "distributed benefits" (Lovins and Yoon 1993) of onsite generation to support local electric distribution.[13]

In these circumstances, one might expect gas companies or third-party entrepreneurs to start providing hookups. A simple credit-card swipe when plugging in the car would automatically handle the gas billing and electricity credit, both at real-time prices. These plus a profit for the entrepreneur could well repay a significant fraction of the depreciation and finance costs of owning the car—together accounting for ~64% of the total cost of the typical American family's second-biggest asset.[14] If even a modest fraction of car-owners took advantage of this opportunity to earn significant profit from that otherwise idle asset, they could well displace a significant portion of fossil-fueled power generation most or all of the time. To utilities now expecting to sell a lot of their surplus electricity to battery-electric cars, and already concerned about stranded generating assets exposed to wholesale competition from combined-cycle gas turbines, such widespread competition from a potentially ubiquitous and flexible power source is hardly a welcome prospect.

The prospect of beating power plants (starting in niche markets with costly electricity or bottlenecked grids but cheap gas) could inspire entrepreneurs to aggregate PEMFC markets for microscale combined-heat-and-power until the fuel cells become cheap enough to use in cars. These two enormous markets could then play off each other: commercialization in buildings will certainly help ensure that hypercars will follow. As in electrical storage, this greatly heightens the likelihood that both will happen. Both are very good news for the environment. Together, displacement of fossil-fueled power plants plus fuel-cell hypercars could reduce by more than half all present climate-threatening emissions from an industrialized nation like the United States.

To help illustrate this conservative scenario for fuel-cell commercialization, Figure 9 illustrates cost reductions as a function of doubling production, given a progress ratio of 82% (Thomas 1997) and an initial cost of $1,500/kW.

Figure 9. Illustrative Fuel-Cell Cost Reduction



Implications for Further Development: Pursuing the Leapfrog to Hydrogen-Fueled Transportation

This analysis argues that the hypercar concept's low-drag, low-load, efficient platform enables the use of gaseous hydrogen fuel and direct-hydrogen fuel cells in passenger vehicles significantly earlier than would otherwise be possible by enlarging the design space in which to use these exciting technologies. Other reasons exist for rigorously pursuing a direct-hydrogen development path. Among these reasons (most of which will be thoroughly described in an upcoming report by DTI for the National Renewable Energy Lab) are:

- Direct-hydrogen operation minimizes the required platinum loadings, and thus cost. Low cost allows greater latitude when sizing the fuel cell to maximize efficiency.
- Reformers and reformate gases would reduce the efficiency of fuel-cell vehicles due to low reformer efficiency, greater vehicle mass, and lower fuel-cell efficiency (which is due, in turn, to hydrogen dilution, low hydrogen utilization, and anode-gas recirculation complexity).
- Fuel-cell vehicles with onboard reformers would also be inferior to direct-hydrogen in other, related ways, including overall mass, cost, complexity, and, importantly, responsiveness.
- When considering the load factors of onboard vs. offboard reformers, the resulting economics clearly favor the offboard application, potentially by one or two orders of magnitude.

Given the potential attractiveness of using pure hydrogen as a transportation fuel, the development of appropriate infrastructures, such as the use of small-scale, mass-produced electrolyzers or reformer "appliances" (Berry 1996, Thomas et al. 1996) or the development of hydrogen corridors or regions (Princeton University's analysis of the LA basin, Ogden et al. 1996), should be more aggressively pursued.

Accordingly, government and industry funding must not be based on an arbitrary system boundary drawn around the vehicle shell; infrastructure cannot be treated separately from vehicle development, because of the interconnectedness of the two. If narrow system boundaries can be overcome and integrated funding priorities can be achieved, then perhaps, with a little help from hypercars, the realization of the many benefits of hydrogen-powered transportation will come to pass—widely, rapidly, responsibly, and profitably.

NOTES

1. Smaller generally means cheaper. Surprisingly, however, RMI has found that cheaper does not necessarily mean less efficient. In other words, *price* and *efficiency* are not necessarily correlated in technological markets.
2. Examples of previous Hypercar Center$^{\text{SM}}$ analyses using these tools, for scenarios where a Stirling engine coupled to a generator provides the onboard electrical power, include Moore (1996a) and Moore (1996b).
3. Although the choice of fiber is still up for debate: "The performance factor of a bladder lined tank using lower strength/less expensive carbon fibers (such as T700S or Panex 33) can match the performance factor of similar tanks with thick liners using higher strength/more expensive carbon fiber (such as T1000G). This is important because tank cost is dominated by fiber cost and the fiber cost per tank for T1000G is currently a factor of three–four times that of T700S or Panex." (Mitlitsky *et al.* 1996)
4. James *et al.* (1994) show that this novel feature, while preserving excellent safety in rigorous tests, raises the tank's performance figure (burst pressure x internal volume / tank mass) from 1.3 to 1.95 megainches or to 49.5 km—some 13 times normal the performance for steel or nearly nine times that for aluminum tanks. Substituting the film for a solid aluminum liner in a wound-carbon tank cuts total tank mass by 50% and materials cost by 36% (James *et al.* 1994).
5. SIMPLEV modeling correlates closely with vehicle test data (Burke 1994) and shows very slightly worse fuel economy than CarSim (Cuddy 1995), a proprietary hybrid-electric vehicle simulator developed at AeroVironment (Monrovia CA) for GM.
6. Electricity at 4¢/kWh contains the same enthalpy (heat content) as oil at $68/barrel—over four times the recent world crude-oil price, or 1.3 times a nominal U.S. taxed gasoline price of $1.25/gal ($0.33/l), but much lower than motor-fuel prices in almost all other industrial countries.
7. A ~10% reduction in mass and in aerodynamic drag (to $C_D = 0.28$, $A = 2.14$ m^2), accompanied by a high $r_0 = 0.0135$ and inefficient accessories were assumed.
8. This is largely because the hydrogen tanks fail gracefully (leak-before-break), hydrogen is buoyant, and its low-emissivity flame has no incandescent soot to radiate infrared and cause burns at a distance. Kuhn (1995) states that in extensive tests, lightweight composite tanks were crashed, crushed, dropped, shot, burned, and blown up, but failed to produce any consequences as bad as those resulting from comparable assaults on ordinary gasoline tanks.
9. Indeed, normalized to the same driving range, the filled hydrogen tank would weigh less than the filled gasoline tank of the conservatively designed hypercars simulated in Moore and Lovins (1995).
10. These figures are not directly comparable not only because the proper comparison is in tractive power delivered to the wheels, but also because the fuel-cell rating is continuous, while the IC engine is designed to produce its rated output for only three minutes at sea level at 20°C.
11. Assuming, for illustration, a 10%/y real fixed charge rate and a 75% capacity factor, such as might be characteristic of an efficient building with fairly long occupied hours.
12. This heat would otherwise need to be dissipated in some other way, so the cost of a heat exchanger cannot be avoided except at extremely small scale.
13. The new Edison EV subsidiary expects to install present-technology Hughes inductive-paddle rechargers, whose electric capacity is broadly comparable, for about $1,000 each, or ~$50/kW. This is a small fraction of the typical value of distributed benefits.
14. For illustration, a 20-kW "mobile power plant" earning an average of, say, 5¢ gross or 2¢ net of fuel cost per kWh—remember, the car would often generate during peak hours, earning real-time pricing premia—for an average of, say, 15 h/d, or 65% of its nominal parking time, would return $2,000 net per year, or over 50% of the total depreciation and financing cost of the average MY1994 U.S. passenger car (AAMA 1994, p. 56).

ACKNOWLEDGMENTS

This research was made possible by the generous support from the W. Alton Jones Foundation. Additional support for the Hypercar Center^{SM} is provided by Changing Horizons Charitable Trust and the Compton, Nathan Cummings, Energy, Hewlett, and Joyce Foundations. The authors would also like to send a heartfelt thanks to: the other members of the Hypercar Center (Jonathan Fox, David Cramer, and Michael Brylawski); RMI editor Dave Reed; Directed Technologies (in particular Sandy Thomas, Brian James, and Ira Kuhn), for enduring the use and "abuse" of their good work; Margaret Steinbuglar and Joan Ogden of Princeton University, for their leadership and instruction; Joseph King, Jr., VP of Technology and Business Development, Al Meyer, Manager of the Transportation Business Unit, and many others at International Fuel Cells; and Ken Dircks, Manager of Customer Support for Ballard Power Systems.

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APPENDIX: MODELING PRINTOUTS

Tractive Loads: 5–6 Occupant PNGV Design Scenario

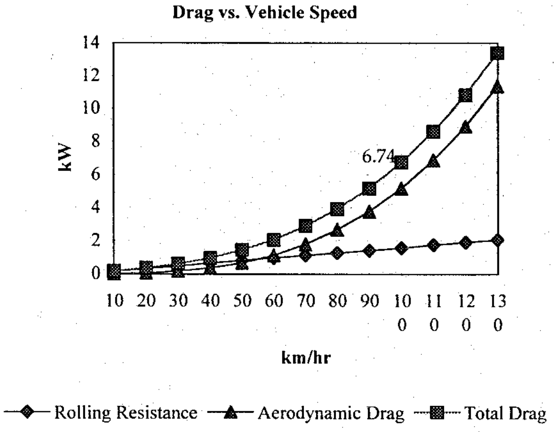
712	0.0056	1.36	56.49	0.2	2.00	0.40

M_{test} (kg) = 848 r_0 with toe-in on road = 0.0062   Grade = 6.5%

Velocity (km/h)	Velocity (m/s)	Rolling R (kW)	Aero Drag* (kW)	Av. Drag (kW)	Total Drag (kW)	@ Grade (kW)
10	2.78	**0.16**	**0.01**	0.08	0.16	1.66
20	5.56	**0.31**	**0.04**	0.26	0.36	3.35
30	8.34	**0.47**	**0.14**	0.48	0.61	5.11
40	11.12	**0.63**	**0.33**	0.78	0.96	6.96
50	13.90	**0.79**	**0.65**	1.19	1.43	8.93
60	16.68	**0.94**	**1.12**	1.74	2.06	11.05
70	19.46	**1.10**	**1.77**	2.46	2.87	13.37
80	22.24	**1.26**	**2.64**	3.39	3.90	15.90
90	25.02	**1.41**	**3.77**	4.54	5.18	18.67
100	27.80	**1.57**	**5.16**	5.96	6.74	21.73
110	30.58	**1.73**	**6.87**	7.67	8.60	25.10
120	33.36	**1.88**	**8.93**	9.71	10.81	28.80
130	36.14	**2.04**	**11.35**	12.10	13.39	32.88

9.08	Current baseline Aerodynamic Drag (kW @ 100 km/hr)
43%	Reduction of Aero Drag from current baseline values
4.50	Current baseline Rolling Resistance (kW @ 100 km/hr)
65%	Reduction of Rolling Resistance from current baseline values
13.58	Current baseline Tractive Load (kW @ 100 km/hr)
50%	Reduction of Tractive Load from current baseline values

Drag vs. Vehicle Speed



*Assumes density of ambient air to be 1.202 kg/m³

See Also: **Tractive Loads for Baseline Vehicle** below

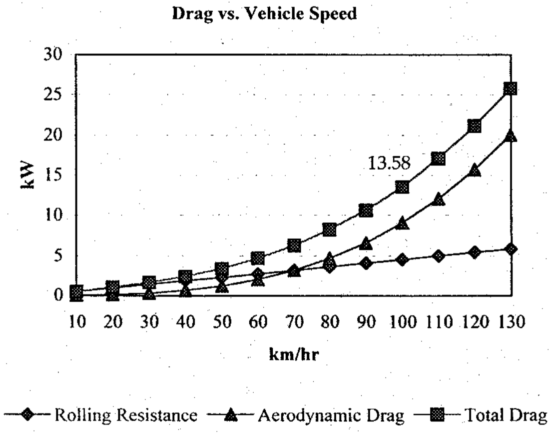
Tractive Loads: Baseline Average 1995 Sedan

M_{curb} (kg)	$r_{0\,tires}$	$\mu_{brngs/brks}$ (Nm)	$f_{r0+\mu}$ (N)	C_D	A (m^2)	C_DA (m^2)
1423.00	**0.009**	**2.6**	**161.97**	**0.33**	**2.13**	**0.70**

M_{test} (kg) = **1559** r_0 tires with toe-in on concrete/asphalt = **0.010**

Velocity (km/h)	Velocity (m/s)	Rolling R (kW)	Aero Drag* (kW)	Total Drag (kW)
10	2.78	**0.45**	**0.01**	**0.46**
20	5.56	**0.90**	**0.07**	**0.97**
30	8.34	**1.35**	**0.25**	**1.60**
40	11.12	**1.80**	**0.58**	**2.38**
50	13.90	**2.25**	**1.13**	**3.39**
60	16.68	**2.70**	**1.96**	**4.66**
70	19.46	**3.15**	**3.11**	**6.27**
80	22.24	**3.60**	**4.65**	**8.25**
90	25.02	**4.05**	**6.62**	**10.67**
100	27.80	**4.50**	**9.08**	**13.58**
110	30.58	**4.95**	**12.08**	**17.03**
120	33.36	**5.40**	**15.68**	**21.09**
130	36.14	**5.85**	**19.94**	**25.79**

Drag vs. Vehicle Speed



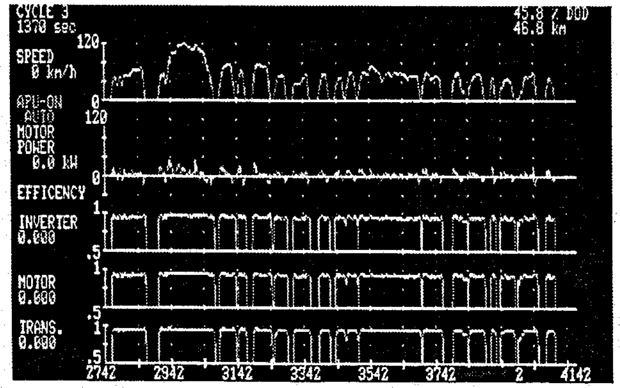
*Assumes density of ambient air to be 1.202 kg/m³

Hill Definition and Cruising-Speed Optimization for Acceleration and Gradability spreadsheet

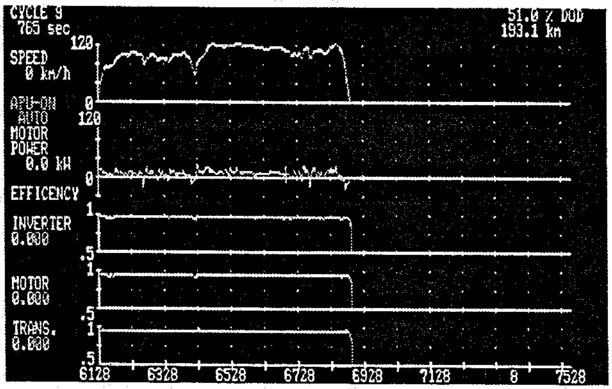
Cd	0.2	r_0	0.0062	Grade	6.5%
A(m^2)	2.00	r_1	5E-06	θ (grade angle)	0.0649087
Test Mass (kg)	848	APU cont. P_{max} (W)	27920	g (m/s^2)	9.81
Gross Mass (kg)	1211	$\eta_{drive\ system}$	91%	**= Motor/controller efficiency @ 55–65 mph and continuous Pmax**	

Lookup Answer:	**Velocity (km/hr)**	**Velocity (m/s)**	**Lookup Answer:**	**Velocity (km/hr)**	**Velocity (m/s)**
@ Test Mass =	112	31	@ Gross Mass =	90	25

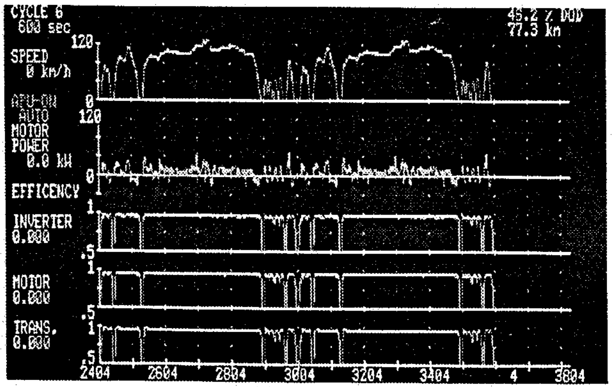
Vehicle speed, motor power, and efficiencies for the motor, power electronics, and single-speed transmission:



Intensified U.S. Federal Urban Driving Schedule (all velocity inputs multiplied by a factor of 1.3).

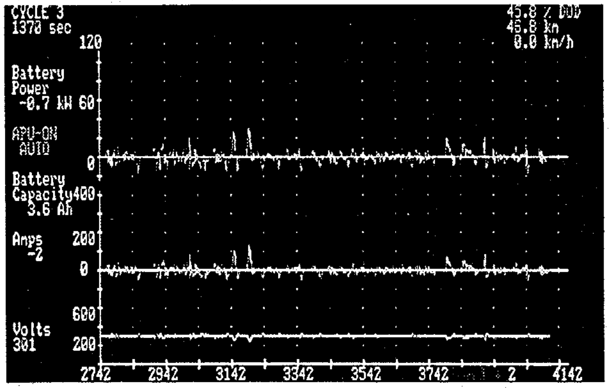


Intensified U.S. Federal Highway cycle (all velocity inputs multiplied by a factor of 1.3).

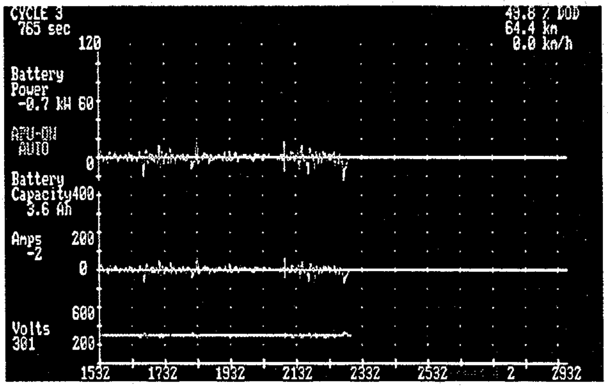


US-06 driving cycle (High-speed and -acceleration cycle developed by the U.S. Environmental Protection Agency to augment the FTP for emissions assessment).

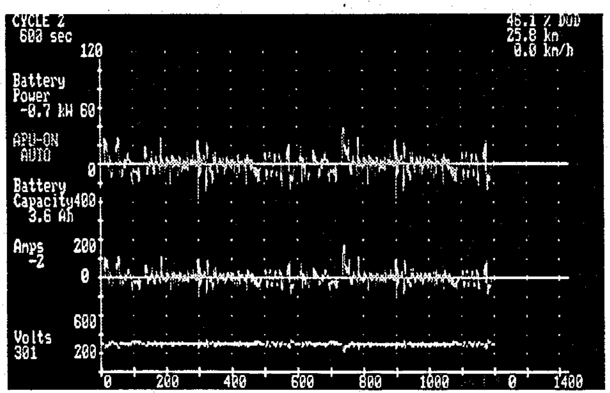
Power, current, and voltage for the load-leveling device (LLD):



Fuel Economy: 123 mpg gasoline equivalent



Fuel Economy: 116 mpg gasoline equivalent



Fuel Economy: 100 mpg gasoline equivalent