Ultralight Hybrid Vehicles: Principles and Design

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ABSTRACT: The *technical* feasibility of superefficient family cars has been demonstrated. Yet it has typically compromised vehicle performance, safety, cost, manufacturability, or marketability. Industry experimentation has tended to focus on improving performance, *or* on implementing hybrid-electric drivesystems in essentially conventional vehicles, *or* on reducing mass and drag, *or* on improving safety—but has rarely attempted to optimize all of these as a system. Maximizing benefits through synergies between platform, chassis-component, and drivesystem design parameters seems poorly understood. Whole-system engineering-design is essential to move toward commercial viability.

Second-by-second simulations and performance modeling provide evidence for automobiles 3–4x more fuel-efficient than today's, with emissions approximating the California Air Resource Board's proposed Equivalent Zero Emission Vehicle requirement for hybrids (~0.1 x ULEV), and with safety, performance, and marketability surpassing that of many current automobiles. The commercial success of such designs depends on the *concurrent* optimization of numerous parameters, with emphasis on tractive- and accessory-load reduction and on component and control optimization. Platform optimization, subject to appropriate design criteria, must precede or accompany new drivesystem technologies, because only tractive-load reduction makes hybrid drivesystems commercially viable. Thus the artful *combination* of hybrid-electric drive with lightweight, low-drag platform design appears requisite to the cost-effective optimization of efficiency, emissions, performance, and safety for production worthy and marketable automobiles.

1. DESIGN CRITERIA

Industry design criteria for efficient vehicles have tended to focus on *limiting compromises* in performance rather than on *improving* it. The one criterion of marketability not typically spelled out is that such vehicles must not only be *equivalent* to those they displace, but be in some way *more* attractive to customers. RMI's analysis suggests that efficient designs could 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, 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 US Partnership for a New Generation of Vehicles) appear essential for the U.S. market and were assumed for this analysis (all improvements are relative to current touring-class production sedans):

- Acceleration from 0–100 km/h in 8.5 s at test mass (half-full fuel tank; two 68-kg occupants), and 12 s at gross mass (five 68-kg occupants; 91 kg luggage).
- Gradability sufficient to maintain 105 km/h on a 6.5% grade at test mass, and 90 km/h at gross mass for 20 min. Acceleration should also be reasonable on grades to facilitate safe merging on steep highway entrance ramps, suggesting 0–100 km/h acceleration in ~15 s at gross mass on a 5% grade.
- 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, handling, and control of noise, vibration, and harshness.
- 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 and emissions specifications for at least 160,000 km, improved service intervals, and comparable reliability and refueling time.
- Equivalent or improved customer features, such as climate control and entertainment systems, and total real cost of ownership.

2. PROPULSION SYSTEMS

Efforts to meet California's Zero-Emission-Vehicle and Ultra-Low-Emission-Vehicle or similar mandates have spawned major advances in propulsion systems: *e.g.*, motors and controllers with high specific power and *system* efficiencies well over 90% for much of their usable range[1–6] and load-leveling devices (LLDs) capable of meeting real-world hybrid vehicle requirements with careful systems integration.[7–10] These advances enable auxiliary power unit (APU) technologies that aren't well suited for conventional cars, but work well in hybrids when accompanied by efficient electric drives. New APU options include gas turbines, Stirling engines, thermophotovoltaic burners, and fuel cells.[11] Among them, Stirling engines capable of maintaining $\eta \geq 0.38$ over a wide range of speeds and loads while far surpassing ULEV standards[11–13], and hydrogen fuel cells with peak η ~0.60 at part load[14], stand out as strong contenders for near- and mid-term introduction, respectively.

Most of these technologies have been around for decades, but until recently were not sufficiently developed or were not enabled by other key technologies for automobiles. Many would still be overly complex, bulky, and probably cost-prohibitive if applied to conventional cars or to heavy battery-electric cars.

2.1. Conventional, Battery, or Hybrid-Electric Drive? Conventional automotive drivesystems based on an internal combustion engine (ICE) mechanically coupled to the drive wheels through a multi-speed transmission are limited by the inflexibility and complexity of mechanical systems and the inability to recover braking energy. To provide ample power for acceleration and gradability, the ICE must be oversized to roughly 10x the 100-km/h, level-ground requirement and 3–4x the 100 km/h, 6% grade requirement. The engine can't be optimized for all of the speed and load range combinations under which it must operate. Efficiency is diminished and emissions are elevated for many segments of the engine map.

Gross oversizing of the engine results both because it must cover the peak load and because peak power occurs at a fixed engine speed that would only be available at all wheel speeds with a continuously variable transmission ratio. While allowing the engine to be optimized for a narrow speed range, continuously variably transmissions are typically inefficient and don't reduce peak power requirements, so their fuel-saving potential is limited. Automatic transmissions with torque converters and gears in series carry the burden of matching engine output and speed at a further efficiency penalty.

Both battery-electric and hybrid-electric vehicles (BEVs and HEVs), unlike conventional vehicles, can recover some braking energy and store it for re-use. BEVs and HEVs, however, satisfy very different criteria.

While electric-only range may appear to be an effective means of reducing vehicle emissions, the electric storage capacity required for even a modest range would preclude meeting many of the above design criteria, thus limiting marketability. Combustion-free range would also be unnecessary under proposed EZEV standards.[15]

BEVs' problems center on performance, range, and cost. BEVs such as the GM EV-1 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. Volvo has concluded that "the cost of most HEVs would be less than that of EVs."[16] The mass of batteries required for even *unacceptable* BEV range drives up the size, mass, and cost of other components for a given level of performance. As designs move towards acceptable range and performance, the mass of the batteries snowballs until almost every component and structure in the vehicle becomes bigger, heavier, and costlier than desirable. The consumer would pay for excessively high-power drivesystem components just to maintain good performance when carrying enough batteries for range. Furthermore, much of the energy in the batteries is required simply to transport the batteries themselves. So like conventional cars, BEVs waste much of their performance and energy storage potential on transporting their own mass.

Flywheels and ultracapacitors have the high specific power needed for performance, but have only enough specific energy capacity to function as LLDs that might extend battery life in a BEV. (Energy storage capacity in flywheels is similar to that of mid-range batteries, but higher unit cost precludes installing numerous flywheels.) Thus range and performance, as constrained by mass, cost, and packaging, appear to preclude BEVs from meeting the design criteria for mass marketing.

The fundamental advantage of HEVs over BEVs is the 10^2x higher usable Wh/kg of fluid fuels over current batteries. HEVs' performance and efficiency are not impaired by massive batteries, nor is their range limited by electrochemical energy storage technology (even if the LLD is electrochemical). Infrastructure and charging limitations are eliminated. Because HEVs' control strategies allow a high-peak-power LLD with little energy capacity (hence much less bulk), energy-storage cost per vehicle can be much lower than for BEVs.

HEVs can easily suffer from compounding size, mass, cost, and added complexity if care is not taken to optimize the design for low mass from the start.[11,17] This has unfortunately been the case for many HEV prototypes. They are typically built from heavy BEVs or conventional production platforms, adding many new components without taking advantage of hybrids' synergistic benefits. Ultralight design is the key to a successful EV, but the EV must be an HEV to be ultralight.

Purpose-built series HEVs, however, can be less mechanically complex than conventional vehicles, particularly with a solid-state APU such as a fuel cell or thermophotovoltaic burner. The multispeed transmission can be eliminated and the starter and alternator replaced by a single alternator that is larger or operates at high speed. If multiple traction motors are used, the differential(s) and perhaps drive axles can be eliminated. Since electric motors are mechanically simple, expenditure on machined parts can be lower than for conventional cars.

2.2. Parallel Hybrid Drivesystems Parallel HEVs (with a mechanical connection between the APU and driven wheels) can tend toward mechanical complexity, typically maintaining that of conventional vehicles by trading a multispeed transmission for one with multiple input shafts or some sort of four-wheel-drive arrangement. There is, however, the potential for using only a single fixed-ratio gear set for each input. This would require a control strategy that runs the APU only at high speeds, increasing the dependence on battery range for urban driving and reintroducing some of BEVs' mass-, power-, and cost-compounding problems.

An additional parallel hybrid drivesystem design (Figure 1) and control strategy, not modeled, might prove advantageous for some technology options. Its principal advantage is potential for improved highway fuel economy. Such a design would function as an on/off series hybrid under low-speed urban conditions and as a power-assist parallel hybrid for highway driving. This would allow the potentially more efficient mechanical connection (a tradeoff between avoided energy conversion steps and increased APU map and possibly additional mechanical losses) of the APU to the drive wheels for highway use. The APU map would be relatively small and avoid the necessity for blending two tractive power sources in urban driving. A small LLD could replace the large, heavy batteries typical of many parallel hybrid designs. The electric portion of the drivesystem might be slightly smaller, depending on the APU control strategy.

Tradeoffs relative to series HEVs would be increased complexity (adding cost), higher emissions and fuel use for some APU technologies, and cumbersome transition to solid-state APU technologies.

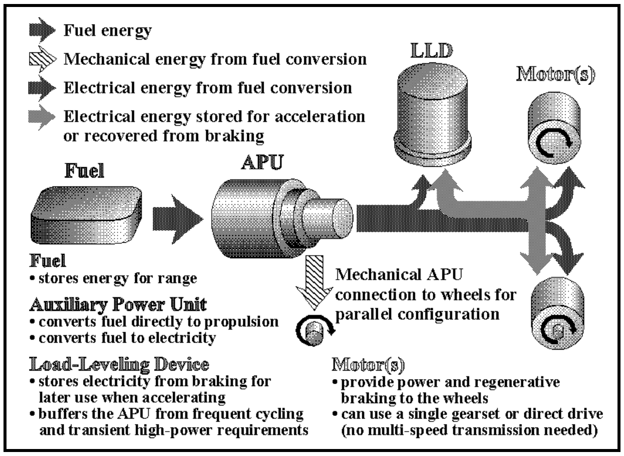

Figure 1 Series and dual-mode-parallel HEV schematic

2.3. Series Hybrid Drivesystems Series HEV drivesystems (with no mechanical connection of the APU to the driven wheels) appear to have only the advantage of regenerative braking, but all the disadvantages of multi-stage conversion (Figure 1). Series HEVs have significant efficiency, emissions, and powerplant-size advantages over conventional vehicles, even if the APU is an ICE. Relative to parallel HEVs, Volvo concluded that series HEVs are considerably more efficient.[17]

An energy conversion penalty exists only to the degree that the product of conversions in the HEV is worse than the product of a conventional ICE (with its broad engine map), multispeed automatic transmission and torque converter, jointed drive shaft(s), and differential. Mechanical APU output (if not solid-state), with a minimized map, is converted to electricity and then back to mechanical energy, which may then pass through a reduction gear and differential. APU output need pass through the LLD only to the extent required by controls to maintain a target state of charge (SOC) and an optimal load range for the APU itself.

Advantages stem from decoupling the APU from peak power requirements and vehicle speed with an LLD and electric drivesystem. The LLD minimizes the load range or engine map. APU peak-power requirements for a series HEV are thus determined more by gradability than by acceleration (which, given our design criteria, would require ~75% more power without an LLD). Cutting peak power requirements toward average loads allows a smaller APU, which can then operate closer to wide-open throttle (if ICE), reducing pumping losses. Minimum load can be a preset level based on the APU's range of best η. Since 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.[18] Decoupling the APU from wheel speed means maximum continuous APU power for hill climbing can be extracted at any speed, rather than only at the vehicle speeds which happen to correspond to output peaks for each gear ratio.

3. VEHICLE DESIGN TO REDUCE TRACTIVE AND ACCESSORY LOADS

The synergistic combination of reduced tractive loads and optimized hybrid drivesystems can improve fuel economy 3–4x or more while making performance criteria more readily attainable. Without extreme measures, constant-speed tractive loads on level ground can be reduced by about 60% (Figure 2). In addition to direct fuel savings and enabling the cost-effective introduction of efficient hybrid drivesystems, emphasizing load reduction will also necessarily result in lower emissions per vehicle-mile, since it affects not *how* fuel is converted but how *much* fuel is converted. Load reduction might also incur little or even *negative* net manufacturing expense if reduced driveline size and complexity saved more than reduced platform drag cost.

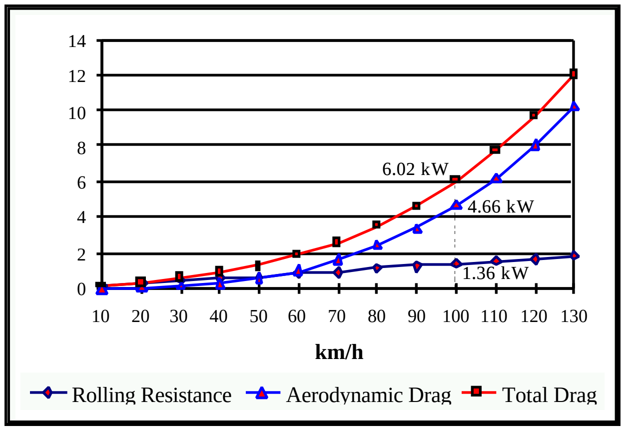

Figure 2 Reduced tractive loads on level ground

3.1. Mass Reduction While HEV fuel economy may be less sensitive to mass reduction than to other variables, such as APU efficiency, the requirement for high acceleration and braking performance, while maintaining reasonable drivesystem component costs and packaging may lead to greater mass reduction. So while direct gains in fuel economy may justify one level of mass reduction, the performance, cost, and packaging benefits that enable efficient hybrid technologies may justify another, and the combined benefits still more.

While made less important by efficient drivesystems, regenerative braking, and low-rolling-resistance tires, mass reduction still contributes significantly to fuel economy. It contributes directly by lowering rolling resistance and power required for acceleration and hill-climbing. It is important, however, to apply a systems approach to mass optimization: the ratio of fuel economy improvement to mass reduction should exceed the ~1:2 achieved by treating mass as an isolated variable.

Mass reduction indirectly aids HEVs' fuel economy by allowing much smaller APU and traction-motor maps. The range between cruising and acceleration loads is compressed, allowing better driving-cycle optimization of component efficiencies. The control strategy turndown ratio (peak-to-lowest-power operation) can be better matched to the APU's highest η. Traction motors can also have lower peak power, thus operating at a higher percentage of peak under typical non-peak loads, which translates to an efficiency gain of about 4–12 percentage points, depending on motor type, design, and loads.[3]

3.1.1. Mass Decompounding Mass decompounding is nonlinear, discontinuous, complex, and inadequately captured by automakers' rule-of-thumb ~1.5x multiplier. For a given payload capacity, the primary and secondary units of mass saved tend to converge over recursive reoptimizations, and more rapidly as payload mass becomes a relatively larger factor than curb mass. (Though the terms 'primary' and 'secondary' imply only a one-step adjustment, the process should include successive recursions until the iterative re-optimizations converge to their asymptotes.) The exception to this is the threshold at which mass reduction allows an economical series hybrid-electric drivesystem with fewer mechanical parts and smaller components.[11]

If material substitution were used to cut body-in-white (BIW) mass by 50% and other components downsized accordingly, with no recursions, 40% curb mass reduction might be challenging. If, however, substitutions are applied to all components, which in turn require less structure, and the process is repeated several times, 45–55+% curb mass reduction appears feasible.

System optimization can lead not only to downsizing, but also potentially to displacing components, saving further mass and cost. Recursive optimization uncovers many linked opportunities for mass and cost savings. Accelerating less mass cuts drivesystem output, reducing driveline-support structural requirements. Smaller peak starting gradability and acceleration loads may also allow a fixed-ratio reduction gear for the traction motor(s), eliminating any multi-speed transmission. The reduced power requirements may even displace all gears with low-speed, high-torque motors. Smaller, lower-power drive components require smaller cooling systems, hence less coolant mass *and* smaller air inlets, reducing aerodynamic drag and thus drivesystem energy and power, making those components smaller and lighter yet. With *gross* vehicle mass equal to the curb mass of today's subcompacts, power steering and power brakes might also be eliminated as they were in the Ultralite, cutting costs and improving high-speed control without sacrificing performance or low-speed maneuverability.

Thus along with mass savings, these options could reduce or eliminate mechanical complexity and costs for transmissions, hydraulic power steering, and perhaps driveshaft and axle joints. Ultimately, the point at which mass reduction minimizes vehicle cost and complexity should be determined before the design is locked into particular structural materials and component choices.

3.1.2. Mass Contribution to Peak Power Mass is the single largest contributor to both intermittent and continuous peak power requirements. For this reason, mass determines the size, and often cost, of the drivesystem components. Maintaining 90 km/h at gross mass on a 6.5% grade requires 3.3x as much power at the wheels (20 kW as modeled) as all level-ground tractive loads at test mass combined. The average power needed for acceleration from 0–100 km/h in 8.5 s at test mass is ~1.6x larger still (39 kW). Reducing *curb* mass 10% lowers power required to maintain 90 km/h on a 6.5% grade at gross mass by ~4% (or ~6% for 5-occupant vehicles with curb mass ~1000 kg) and the power required for 8.5-s 0–100 km/h acceleration at test mass by ~8.5%. Thus payload dilutes the effect of curb mass reduction.

3.1.3. Body-In-White Structure: Materials and Mass Reduction Technologies for mass-saving and parts-consolidation with high-strength and carbon steel, and for producing and fabricating aluminum, and polymer or metal-matrix composites, contribute to the potential for 40–55% curb-mass reduction *without* downsizing.[11,19–22]

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.[23] 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, commissioned by AISI, has calculated the "realistic achievable potential" for BIW mass reduction using steel to be 15–20%, with a theoretical maximum around 30%.[24]

Ford's 199-kg Taurus AIV (Aluminum Intensive Vehicle) BIW is 47% lighter than the standard Taurus BIW.[20] This was accomplished without even taking full advantage of mass decompounding 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-seat hybrid ECC (Environmental Concept Car) also weighs ~200 kg, has sufficient strength to carry 350 kg of batteries plus its payload, and includes extensive provisions for crashworthiness.[25] BIW mass reductions up to 55% using aluminum may be technically feasible for high-volume production by 2000, although the economics of doing so are still uncertain.[21]

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.[22] With proper design, specific crash-energy absorption can be two[22] to five[26] x that of steel. Molding properties of composites provide greater styling flexibility. Assembly steps, finish processes, and tooling can be reduced by an order of magnitude through parts consolidation and lay-in-the-mold finish coatings, potentially eliminating material cost penalties.[19] Industry analysis shows potential for ~60–67% BIW mass reduction using carbon-fiber reinforced composites.[27] These materials do, however, face manufacturing-engineering challenges.

3.1.4. Decoupling Mass From Size Using lightweight materials for the BIW largely decouples vehicle mass from size, allowing substantial mass reductions without downsizing. Thus crash ridedown distance can be maintained or even increased (partly because drivesystem components could be smaller and more modular) relative to current midsized sedans. This is particularly true for polymer composites, with their exceptionally high specific strength.

3.1.5. Design and Materials for Safety Lightweight vehicle design, while presenting new challenges, does not preclude crashworthiness. Using proven technologies for energy absorption, force-limiting occupant restraints, and rigid passenger-compartment design, light vehicles can surpass the safety of today's cars in many types of collisions.[11,22,26,28–30] High-speed head-on collisions with, and side impacts from, *significantly* heavier collision partners, might be effectively dealt with through innovative and careful design, such as force-limiting restraint systems, large crush zones with multiple stages of increasing stiffness, and dedicated polymer-composite energy absorbing structures.[id.] A similar strategy could be used for the rear and side. Intrusion prevention, restraints such as airbags, and interior bolsters should be emphasized for side impacts where crush space is limited.

Though statistical evidence is clouded by other factors such as driver risk-averseness and poor braking performance in economy cars, lightweight design *can* also improve maneuverability and stopping distance, potentially allowing the driver to avoid some collisions.

To avoid rejection by consumers, light hybrid vehicles should provide at least equivalent safety when colliding head-on with vehicles of average or higher mass at the time of introduction. This may require absorption of several times the static fixed-barrier crash energy in a collision with a vehicle weighing twice as much.

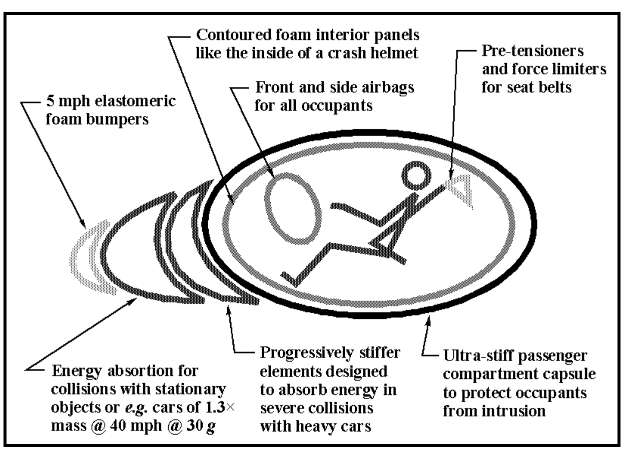

Figure 3 Multistage energy-absorption schematic

3.1.6. Low-Mass Vehicle Dynamics Improved handling, maneuverability, tire adhesion, and braking are possible with low curb mass, new tire compounds, and HEVs' potential for ultra-responsive 4-wheel ABS and traction control. Depending on gross-to-curb-mass ratio, gross mass and mass distribution could vary considerably with payload, possibly requiring active suspension. However, HEV drivesystem modularity and light BIW materials can provide a lower center of gravity. High specific strength materials allow very stiff passenger compartment designs improving suspension performance and ride without excessive mass. Ultralight wheels (perhaps carbon-fiber composite over a magnesium skeleton for graceful failure), aramid-belted tires, hub carriers, and brakes (with metal-matrix calipers and carbon/carbon-silicon-carbide rotors) can keep the spring-to-unsprung-mass ratio high enough (>10:1) for excellent ride and suspension performance. Locating brakes inboard on driven axles can further reduce unsprung mass, while improving aerodynamics. Fully electric power steering can be provided only as needed at low speeds, high gross mass, and in tight turns. Many such options exist for suspension, steering, brakes, wheels, and tire.[11]

3.2. Rolling Resistance and Tires Rolling resistance is the product of vehicle mass times the coefficient of tire rolling resistance (r_0), plus parasitic losses from wheel-bearing and brake drag. The power required to overcome it rises linearly with vehicle speed. Parasitic losses can be extremely small with high-quality double offset ball bearings and calipers designed to retract brake pads fully from the rotors. Rolling resistance reduction of ~50–70% from average appears desirable to meet industry goals and our design criteria (Volvo claims a rolling resistance reduction of 50% using tires from Goodyear on its 1,580-kg hybrid ECC—a noteworthy accomplishment, given that the ECC is ~130 kg heavier than average midsized sedans). Goodyear tires developed for the GM Impact prototype BEV achieved r_0 of 0.0048 at 65 psi,[31] but partly at the expense of traction. The Michelin tire developed for GM's EV-1 production version does nearly as well (r_0 0.0062 in coast-down testing) without sacrificing traction.[32]

3.3. Aerodynamics: Frontal Area Assuming that the vehicle must seat five in a sedan format (two seating rows), the practical limit for the frontal area (A) of the *interior* space is ~1.65 m^2. While roof and floor sections 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 interior bolsters for side impacts, is ~0.1 m^2 each. Roof curvature adds another ~0.05 m^2. So an appropriate practical-limit dimension for A in a 4–5 occupant design would be ~1.9 m^2 (~0.23 m^2 less than the '95 Ford Taurus).

Well-packaged prototypes such as the Esoro H301, GM Ultralite, and Renault Vesta II, with respective A of 1.8, 1.71, and 1.64 m^2, have relatively upright, comfortable seating, but for just four adults. Some of these vehicles have thin door sections that might appear flimsy to customers. The advantages of packaging improvements may also be used up by side impact protection and generous interior space, if such vehicles are introduced at the high end of the market.

Figure 4 Marketable aerodynamic design

3.4. Aerodynamics: Drag Coefficient Aerodynamic drag varies as velocity cubed and is the largest load at highway speeds on level ground. For an average 1995 model cruising at 100 km/h, aerodynamic drag typically consumes well over twice the power of rolling resistance. Given the limits of *A* (§3.3), lowering the drag coefficient (C_D) is the principal way to reduce this load. The C_D results from combined form, interference, induced, surface, and internal-flow drag.

Cab-forward design with a smooth underbody (from the start of design to avoid the mass, cost, and complexity of add-on panels) that tapers towards the rear and has clean trailing edges can substantially reduce form drag. Interference drag is reduced by careful treatment of body seams, windows, side mirrors, wipers, wheel wells, suspension components, and airflow exiting from the interior and cooling systems. Lift-induced drag would also be reduced by smoothing the underbody flow, and by sloping the underbody surface upward toward the rear to help neutralize the pressure differential typically resulting from low-pressure, high-velocity flow over the body and high-pressure turbulent flow underneath. Cutting surface drag would depend on reducing skin friction with specially textured surfaces that provide passive boundary-layer control. While textured surface finishes might pose marketing challenges on the upper body, underbody flow could still be improved. Internal-flow drag can be minimized by smoothing internal flow paths and downsizing cooling inlets for the reduced cooling loads from lower tractive loads and an efficient drivesystem.

Rather than smooth the underbody and attempt to tuck chassis components up out of the flow, industry strategy has tended towards air dams below the front bumper to force much of the flow around the vehicle. This increases *A* and leads to the erroneous notion that achieving very low aerodynamic drag requires extremely low ground clearance. Allowing the airflow to pass under the car only slightly increases frontal area by exposing more if the tires and can eliminate lift-induced drag.[33] HEVs have fewer and smaller components, which otherwise could complicate smoothing the underbody.

Many small (2–4 seat) prototypes have demonstrated C_D ~0.18–0.19. This is somewhat easier with midsized cars because the elements that cause interference drag are physically smaller relative to the frontal area. Longer vehicles for crush-stroke optimization also make low form drag more readily achievable. If traditional appearance and stylistic flexibility take precedence, however, C_D might bottom out around 0.20.

3.5. Glazing and Accessory Loads Reducing accessory loads becomes important at low tractive loads. Spectrally selective glazing, insulative body panels, breathable seat materials, photovoltaic-powered automatic ventilation fans, and other design options can all reduce cooling and heating loads, thus reducing the mass, bulk, and power requirements of the HVAC system. Careful system integration can cut the fuel, weight, and cost penalties of interior heating and cooling by ~50–75+%.[34–36] As modeled, a 250 W reduction in accessory loads improves fuel economy 8% on the FUDS x 1.3 driving cycle.

4. MODELING

To explore these ideas quantitatively, RMI developed parametric spreadsheets for use in combination with SIMPLEV—a second-by-second component-matrix-based model[37]—for relatively comprehensive modeling of vehicle performance, fuel economy, and emissions; details are available from the author.

4.1. Summary of Modeling Inputs

Occupants:	4–5 (2 x 68 kg @ M_{test})	$A_{frontal}$	1.9 m^2
M_{curb}	585 kg	C_D	0.19
M_{test}	721 kg	$r_{0\ tires\ (SAE)}$	0.0056
M_{gross}	1016 kg	$r_{0+road\ \&\ toe\text{-}in}$	0.0062
$I_{rotational}$	11.0 kgm^2	r_1	1.6 E^{-5} s/m
$M_{test\ effective}$	858 kg	$\mu_{brks\ \&\ bearings}$	1.36 Nm
$Ratio_{sprung:unsp.}$	10:1	$P_{HVAC\ \&\ access.}$	500 W

APU:	Stirling Thermal Motors, Ann Arbor, MI
Input matrix	engine/generator η & emissions @ % load
Power	26 kW continuous @ STP
Efficiency	40% peak at shaft, 35% average at DC out
APU Mass	47 kg w/custom auxiliaries, some MMCs
LLD:	Pb-A: Bolder Tech., Wheat Ridge, CO
Input matrices	V & IR @DOD; *C* rating & Peukert const.
Specific power	800 peak W/kg from 10–70% DOD
Specific energy	30 Wh/kg @ 25*C* (30 A), 36 Wh/kg @ *C*/2
Pack voltage	300 VDC nominal
Peak power	28.8 kW @ 300 VDC
Energy capacity	1.3 kWh (450 80-g, 2-V, 1.2-Ah cells)
Mass	42 kg including cell connectors
Motor:	PM: Unique Mobility, Golden, CO
Input matrices	η @ torque & speed; torque @ speed
Starting torque	226 Nm
Gradability power	22 kW (continuous @ 6,000–8,000 rpm)
Peak power	48 kW (maximum for acceleration)
Mass	37.5 kg (scaled to 90% of 53 kW)
Motor Controller:	Digital: Unique Mobility, Golden, CO
Input matrix	η @ motor torque and speed
Voltage range	200–400 VDC
Maximum current	300 A (starting-torque limit)
Mass	13.6 kg (scaled for use with APU & LLD)
Transaxle:	based on data for Chrysler ETV-1
Input matrix	η @ torque & speed (η + 2% ≈ 0.95 av.)
Gear ratio	6.6:1 fixed ratio (single-stage reduction)

SIMPLEV modeling correlates closely with vehicle test data[38] and shows very slightly worse fuel economy than CarSim[39], a proprietary HEV simulator developed at AeroVironment (Monrovia, CA) for GM.

The U.S. Federal Urban (FUDS) and Highway Driving Cycles were simulated, along with versions of those cycles with all second-by-second input velocities multiplied by a factor of 1.3 to represent more realistic driving patterns. This is somewhat more conservative than the EPA correction factors applied to fuel economy results, and has the advantage of simultaneously correcting power, energy-storage, and emissions parameters.

4.2. Performance and SIMPLEV Modeling Results:

Acceleration 0–100 km/h:	@ test mass	8.6 s
	@ gross mass	11.6 s
	@ test mass on 5% grade	10.4 s
	@ gross mass on 5% grade	15.4 s
Starting grade:	@ gross mass	30 %
Velocity on a 6.5% grade:	@ test mass	104 km/h
	@ gross mass	86 km/h
Regen braking from 40 km/h:	@ test mass	0.31 *g*
	@ gross mass	0.23 *g*
Max. Δv for frontal crush:	@ test mass and 30 *g*	65 km/h
	0.55 m @ 30 *g*, 0.3 m @ 40–50 *g*	88 km/h
offset strike of 50% crush area	@ test mass and 15 *g*	km/h
	0.55 m @ 15 *g*, 0.3 m @ 20–25 *g*	62 km/h

Driving cycle:	km/l	l/100km	mpg	55% City/45% Hwy
FUDS	44.7	2.24	105	46.5 km/l
Highway	48.7	2.05	115	110 mpg
FUDS x1.3	38.7	2.58	91	38.2 km/l
Highway x1.3	37.6	2.66	88	90 mpg

Driving cycle:	HC	CO	NO_x	
FUDS	0.0002	0.009	0.024	g/km
Highway	0.0002	0.008	0.022	g/km
FUDS x1.3	0.0005	0.011	0.026	g/km
Highway x1.3	0.0008	0.016	0.025	g/km

5. CONCLUSIONS

Though not quantitatively definitive, this analysis demonstrates the value of combining lightweight, low-drag, thermally efficient platform design with efficient hybrid drives. This technology fusion substantially improves fuel economy and emissions without compromising safety, performance, and marketability. There appears to be considerable potential for improving *all* of these parameters simultaneously and synergistically.

While not contributing much more fuel economy per change in load fraction than does the drivesystem per change in efficiency, tractive load reduction stands out as the largest untapped source of fuel economy improvement. Because the required drivesystem power output is reduced, vehicle emissions necessarily decrease at least in proportion to tractive load reduction.

Introducing many new technologies and design changes at once implies high risks and shifts in manufacturing investment. But the synergies between some of the constituent technologies appear to require their introduction as a system rather than separately. Careful attention to such details as body seams, accessory loads, brake drag, and wheel-bearing friction is essential. Every parameter and component must be optimized as part of the whole system if the design is to be successful.

ACKNOWLEDGEMENTS

This research was supported by The Compton, Nathan Cummings, Energy, W. Alton Jones, Joyce, and Surdna Foundations and Changing Horizons Charitable Trust. Travel was sponsored by Mitsubishi Electric America and Mitsubishi Motor Sales America. Many thanks to the author's colleagues and numerous advisors in the field.

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