Edited by **Kevin Jost**

CPI takes new direction on Li-ion batteries

The global recall of lithium-ion (Li-ion) batteries that is rocking the consumer-electronics industry brings some irony to hybrid-electric vehicle (HEV) engineers.

Like everyone who relies on laptop computers as their main tools-of-the-trade, hybrid engineers have been swapping out their laptop batteries for replacements, as stipulated by the recall, as a precaution against potential fire caused by overheating.

This comes at a time when most major automakers are betting on Li-ion to replace nickel metal-hydride (NiMH) as the predominant battery chemistry for HEVs within a few years.

"When I was on **Ford**'s hybrid program in 1998, we didn't trust Li-ion batteries because of the fire risk," said Prabhakar Patil, CEO of Compact Power Inc. (**CPI**), which is developing Li-ion batteries for automotive use.

CEO Prabhakar Patil was Chief Engineer of Ford's Escape HEV program before joining CPI last year.

Lithium also had a cost disadvantage compared with NiMH, said Patil, whose 27 years at Ford included stints as electric-vehicle program manager and Chief Engineer of the Escape HEV.

"But the technology has changed dramatically," he said. "We're confident of durability and safety. Costs are coming down. Li-ion is being readied for production in hybrid vehicles beginning in 2010."

With batteries being roughly 33% of hybrid-electric driveline cost, and the price of nickel rising sharply on global commodity markets in recent years, improvements in HEV performance, operating range, and value are anticipated from a switch to Li-ion, according to **General Motors**, **Honda**, and **Toyota** engineers.

Other major hybrid battery makers, including **Hitachi**, **Johnson Controls-Saft**, **Panasonic EV**, and **Sanyo**, are also investing heavily in Li-ion development.

The battery suppliers are involved with Li-ion programs beyond the new HEVs. For example, a Saft Li-ion battery pack is part of GM's Sequel fuel-cell concept vehicle that will enter low-volume production in the 2010 time frame.

CPI-LG Chemical's thin, flat "stack-and-fold" cell design will further benefit Li-ion's two to three times greater energy and power density compared with NiMH cells, the company says.

Founded in 2001, CPI is the North American subsidiary of **LG Chemical**, the petrochemical division of Seoul-based **Lucky Goldstar**. LG Chemical is the world's third largest supplier of Li-ion batteries (after Sanyo and **Sony**), producing 20 million cells per month, primarily for consumer-electronics applications.

According to Patil, LG Chemical saw the promise of Li-ion in the early 1990s and never invested in NiMH technology. By 2005, the year Patil joined, CPI's business was focused strictly on automotive battery R&D and supply, including that for passenger vehicles, medium- and heavy-duty trucks, and off-road equipment.

"Our plan is to produce turnkey automotive battery systems in North America—battery packs, plus integrated cooling and control systems," Patil said. The battery cells will be manufactured in South Korea.

Validating and verifying Li-ion for automotive applications are the remaining hurdles in bringing the new chemistry into hybrid cars and trucks.

"We must prove unquestionable robustness over a 15-year calendar life," said Martin Klein, CPI's Director of Engineering.

Battery makers are working to establish the optimum chemistry, particularly cathode material, overall configuration, and battery management system for Li-ion types, Klein said.

He said CPI uses a manganese-based cathode material, rather than the $LiCoO_2$ widely used in laptops, mobile phones, and other portable electronic devices. $LiCoO_2$ contains cobalt, a strategic material that is costly ($40/kg) and does not tolerate abuse due to internal shorting and overcharging, which can mitigate fire and explosions—known to battery engineers as "thermal runaways." The manganese-based material includes additives to boost calendar life under temperature.

CPI's "flat" battery-cell construction differs from the standard cylindrical metal cans commonly used in NiMH batteries.

Research Director Mohamed Alamgir (left) and Engineering Director Martin Klein are confident Li-ion is nearly ready for HEVs.

Li-ion vs. NiMH		
Attribute	NiMH	Li-ion
Energy density, W·h/kg	80	200
Power density, W/kg	1600	>3000
Volumetric energy density, W·h/L	200	550
Cost, $/kW·h	35	30-35
Self discharge (per month), %	15	5
In/out efficiency, %	90	>95
Temperature range, °C	-10 to +40	-30 to +50
Cycle life	900 (EV); 300K (HEV)	1000 (EV); 300K (HEV)
Calendar life, yr (CPI data)	>10	>10

"Flat cells are much more package-efficient than cans," said Mohamed Alamgir, Director of Research. "They're also less costly and not prone to corrosion."

CPI, with LG Chemical, has developed what it calls a "stack-and-fold" design, in which layers of electrodes are ganged in a thin, flat configuration resembling a single-portion pouch of instant coffee. This design costs less to produce than a metal can, Alamgir said, and its greater surface area provides more power while aiding thermal management.

The pouches are also more robust—the design keeps the electrodes aligned under all conditions. CPI engineers claim that the semi-permeable insulating membrane separating the electrodes in LG Chemical Li-ion cells is mechanically and thermally superior to separators used in other Li-ion cells.

"It's a key to battery safety," said Patil.

Accelerated testing of the aluminum-polymer lamination that protects the cell has shown a predicted seal life of 15 years, he said.

CPI has developed and will supply its own microprocessor-based battery management system.

Patil stressed that CPI intends to verify all of its claims of battery performance with the U.S. Advanced Battery Consortium (**USABC**, the battery R&D arm of **USCAR**), which has established third-party test procedures.

"When I was on the vehicle side, I never trusted what battery suppliers told me," Patil said. "As an industry, I regret to say our claims have often been inconsistent at best."

Klein injected a quote typically attributed to Thomas Edison, who allegedly said, "There are liars and there are battery manufacturers."

"We do not intend to perpetuate that image," he said.

Lindsay Brooke

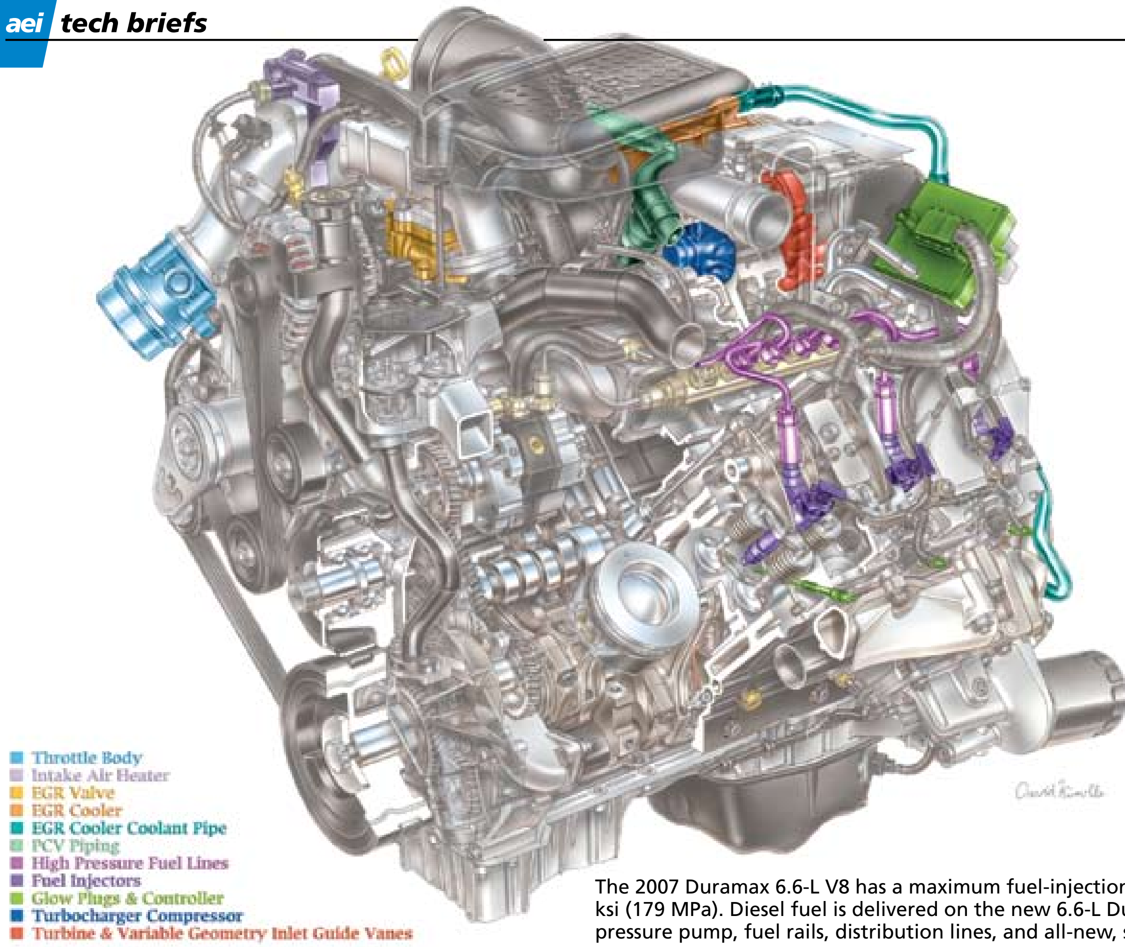
GM developing light-duty diesel V8

The vacant spot in **General Motors**' global diesel engine lineup gets filled after 2009 when the automaker adds a light-duty diesel V8 to its powertrain portfolio. There is little doubt that GM wants this future turbocharged diesel to be viewed as a viable alternative to a gasoline V8. The new diesel will have noise and vibration cues approaching that of a gasoline engine. The diesel will package in a Small Block gasoline V8 engine envelope, and it will be 50-state emissions compliant.

"This is an all-new GM design," said Charlie Freese, GM Powertrain's Executive Director of Diesel Engineering. At this point, GM officials are being coy about the future engine's displacement. "It's more than 3.0 L and less than 6.6 L," Freese said. GM's current global diesel engine product line consists of 17 variants from six base architectures, ranging from a 1.3-L four-cylinder to a 3.0-L V6, then jumping to a 6.6-L V8.

The patents-pending V8 is targeted to deliver "industry-leading power and torque," according to Freese. The dual-overhead cam, four-valve engine also will

GM's Gary Arvan flanks the automaker's 2007 Duramax 6.6-L turbocharged diesel engine, which uses a revised E35 controller with new control software to meet emissions requirements.



The 2007 Duramax 6.6-L V8 has a maximum fuel-injection pressure greater than 26 ksi (179 MPa). Diesel fuel is delivered on the new 6.6-L Duramax V8 via a higher-pressure pump, fuel rails, distribution lines, and all-new, six-hole fuel injectors.

feature new-for-GM elements, including a compacted graphite iron (CGI) block and fracture-split main bearing caps.

The turbocharged engine will employ a high-pressure common-rail fuel system that can inject fuel five times per combustion event to control noise and emissions. As showcased in a **Buick** Rainier test mule, the diesel engine produces 330 hp (246 kW) at 4000 rpm and 520 lb·ft (705 N·m) at 1800 rpm. A diesel particulate filter, oxidation catalyst, and selective catalytic reduction (SCR) catalyst with urea injection are used on the demonstration vehicle's engine to address emissions.

"It's a very special engine," said Gary Arvan, GM Powertrain's Chief Engineer of V8 Diesel Engines. "It doesn't have any compromise. It's a very refined engine." The new engine is slated for use in pickup trucks with a gross vehicle weight rating less than 8500 lb, according to GM officials.

GM's Duramax 6.6-L V8 turbodiesel, which debuted in 2001, enters 2007 with numerous alterations for 50-state emissions compliance. The revised engine has a 50% reduction in NOx and a 90% reduction in particulate matter compared to the 2006 powerplant.

A diesel particulate filter was added to reduce soot and particulate matter. The engine continues to use an oxidizing catalyst, but it has been modified to handle the increased workload necessary for regeneration of the particulate filter. An intake throttle was added to provide smoother engine shutdown, support diesel particulate filter regeneration, and reduce emissions. Exhaust gas recirculation (EGR) cooling capacity was increased via use of a "finned high-performance heat exchanger versus the 2006 engine's tube-in-shell cooler," said Arvan.

Turbocharger efficiency was improved "through geometry changes to the turbine wheel, compressor wheel, and variable nozzle turbocharger mechanisms," said Arvan. The turbocharger gives the engine a maximum boost of 20 psi (138 kPa).

The Duramax also features improved sealing beads on the cylinder head gasket, enhanced engine control software, and a more robust structure. "In order to meet the 2007 emissions, we're using more EGR at full power, which results in increased cylinder pressure. And because of the increased cylinder pressure, we've had to improve the engine structure—mainly the cylinder head and block geometries," said Arvan.

The engine's applications for 2007 are in heavy-duty **Chevrolet** Silverado and **GMC** Sierra pickup trucks, medium-duty Chevrolet Kodiak and GMC TopKick pickup trucks, and Chevrolet Express and GMC Savana full-size vans.

According to Arvan, the 2007 engine for the Kodiak and TopKick with LYE option produces 330 hp (246 kW) at 3000 rpm—vs. 300 hp (224 kW) at 3000 rpm in 2006—and 620 lb·ft (841 N·m) at 1600 rpm—vs. 605 lb·ft (820 N·m) at 1600 rpm in 2006. Final power ratings for the engine used in the Silverado and Sierra as well as the Express and Savana will be released at a later date.

"The 2007 Duramax 6.6-L turbocharged V8 meets the on-highway, heavy-duty 50% phase-in for the **EPA**'s 2007 NOx requirements, and it meets the 2007 particulate matter standard," said Arvan. In addition to the engine revisions, the use of reformulated, ultra-low-sulfur diesel fuel—limited to sulfur content of 15 parts per million (ppm) vs. the past standard of 500 ppm—is required to meet the new emissions standard.

Kami Buchholz

Eaton uses hydraulics for hybrid

A joint venture between **Eaton**, **United Parcel Service** (UPS), and the U.S. **EPA** has produced a pair of ubiquitous brown UPS delivery trucks that have achieved eye-popping improvements in efficiency.

The trucks feature hydraulic hybrid drivetrain technology claimed to reduce fuel consumption in heavy vehicles by as much as 70%, a fact that makes the technology very attractive to commercial vehicle operators that are very sensitive to fuel costs.

The system in the UPS trucks replaces the transmission with an engine-driven hydraulic pump that pressurizes a high-pressure accumulator. While the hydraulic fluid is not compressible, nitrogen gas in the accumulator is, and that is what stores the energy.

Only lettering on the side distinguishes this UPS parcel delivery truck as an innovative hydraulic hybrid that can slash fuel consumption by 70% compared to a conventional truck.

The high-pressure accumulator is plumbed to the pump motor connected to the drive axle, which converts the hydraulic pressure into rotating power for the wheels when power is needed. Fluid moves from there to a low-pressure accumulator that supplies the pump with fluid for charging the high-pressure accumulator.

Under deceleration, the rear drive pump motor reverses its function, charging the pressure stored in the high-pressure accumulator.

The accumulator can store enough energy to propel the truck a distance of several hundred feet, according to Robert Hall, Fleet Environmental Manager for UPS. That translates into a 50% reduction in engine-running during stop-and-go urban delivery conditions.

The system has been developed under the EPA's Clean Automotive Technology Program with participation by **International Truck and Engine**, the **U.S. Army**'s National Automotive Center, **FEV**, **Southwest Research Institute**, and **Morgan-Olson**.

The system, if put into production, would add about $7000 to the cost of such trucks (less than 15% of the base truck's cost), but return $50,000 in fuel savings over the trucks' 20-year lives, according to the EPA.

Hydraulic hybrids offer the same benefits and functions as the better-known electric hybrids, including regenerative braking and engine stop-start, as well as propulsion by means other than the vehicle's internal combustion engine. The regenerative braking is particularly effective for hydraulic hybrids compared to electrics, because the hydraulic system can accept large amounts of energy very quickly. Electric hybrids have a limited rate of recharge for their batteries.

This makes hydraulics particularly well-suited to vehicles such as commercial trucks as well as large passenger vehicles and pickup trucks, because their heavier weight means more energy is recovered during braking, according to David Haugen, Manager of the Technology Development group at the EPA's National Vehicle Fuel and Emissions Lab in Ann Arbor, MI.

As an example, the **Toyota** Prius' electric-hybrid drivetrain recaptures energy while braking with an efficiency of 25-30%. In comparison, the hydraulic hybrid system is 70% efficient in capturing energy during regenerative braking, he said.

The Eaton system is scalable for use in vehicles of all sizes, Haugen said. But its advantage over electric hybrids is more pronounced in heavier vehicles.

"Hydraulics are familiar, relatively simple, and quite low cost," observed Haugen. "They have a cost advantage over any other technology that could be used for a series hybrid."

A prototype **Ford** Expedition that used a series-type hydraulic hybrid system, similar to that used in the UPS truck, had much lower incremental cost than today's parallel electric hybrids, which cost thousands of dollars more than their conventionally powered base vehicles.

"The estimates for mature-volume production costs were about $700 compared to the base vehicle," said Haugen. That cost, he added, includes the savings from the elimination of the conventional automatic transmission.

A series-hybrid configuration was chosen for the UPS truck rather than a parallel-type layout because of its greater potential efficiency, Haugen said. That's because, when it is decoupled completely from the wheels, the engine is able to run at its most efficient speed to meet emissions requirements.

"The engine doesn't need to instantaneously respond to the driver's request for more speed," remarked Haugen. "The engine's job is to ensure that the hydraulic accumulators don't deplete down to the point that they can't propel the vehicle."

As a result of this disconnect between the engine and the vehicle's speed, the driving experience takes getting used to. "It does feel odd," said Haugen. "That disconnect between what you've become accustomed to hearing and feeling becomes even more exaggerated as you work harder to decouple the engine from the drivetrain in pursuit of fuel economy."

The driver's experience isn't particularly relevant to operators of commercial fleet vehicles. But for vehicles marketed to consumers, it could affect customer acceptance. "It does require an adjustment," Haugen said. "But as an engineer, I like anything new and different."

Both prototype trucks employ an International DT466 I6 diesel engine. One of them is a test bed for clean diesel technology in addition to having a hybrid powertrain, said Brad Bohlmann, Advanced Marketing Manager for the Fluid Power group.

The goal is for the truck to meet EPA emissions requirements for 2010, he said, but the company is not ready to discuss details of the technology.

Meanwhile, Eaton is also developing a parallel-hydraulic hybrid system for commercialization that will be marketed in 2007 for refuse trucks, he said. Eaton has also built electric-hybrid delivery trucks that **FedEx** is testing in its fleet.

Dan Carney

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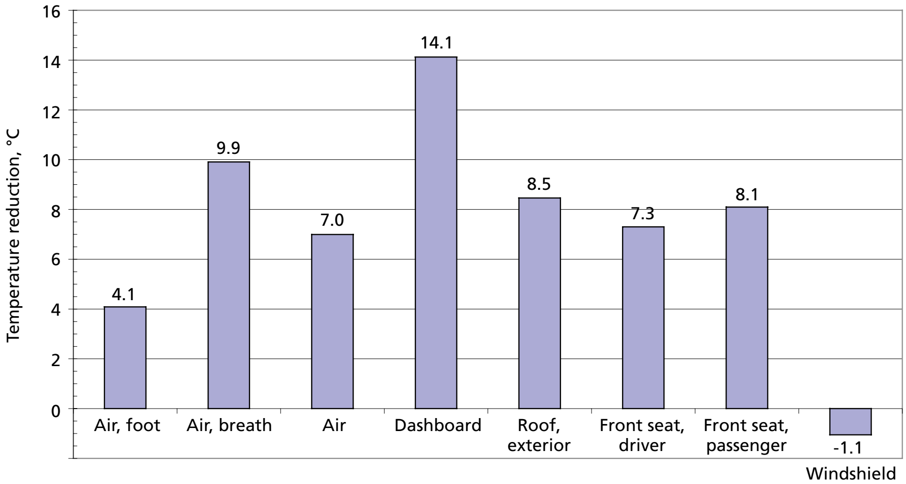
NREL looks at reduced A/C loading

Automakers looking to reduce global warming emissions from air-conditioning systems have been focusing on improving the efficiency of compressors and heat exchangers, reducing leakage of R-134a, or even using another refrigerant with lower effect. However, reducing passenger-cabin heat gain and venting air heated during hot soak would permit use of a smaller-capacity A/C system. A 26% saving in fuel used to operate the A/C over the federal drive cycle was indicated by this approach in a demonstration project of the U.S. **DOE**'s NREL (National Renewable Energy Laboratory).

NREL retrofitted a 2005 **Cadillac** STS with special window glazing, a headliner insulator, and a heat-reflective roof film, all from **3M**, and a **Webasto** sunroof with a solar-electric-powered fan to vent cabin air heated during hot soak from sunload. This vehicle was paired with a standard STS, and both were hot-soaked simultaneously in sunny Golden, CO, in ambient temperatures of 90-95°F (32-35°C), explained NREL Senior Engineer Larry Chaney. Temperature measurements were taken throughout the cabins, including comfort levels during cool down of a front "passenger," ADAM, a sensor-equipped dummy capable even of "sweating."

The NREL's retrofitted STS demonstrated how reducing passenger-cabin heat gain and venting hot-soak air would permit use of a smaller-capacity A/C system.



Cabin temperature reductions (shown in chart) in NREL testing range from 4.1°C (7.4°F) at foot level to 14.1°C (25.4°F) at the dashboard.

The measurements showed that the steps taken in the special STS had reduced interior temperatures by a range of from 4.1°C (7.4°F) at the feet to 14.1°C (25.4°F) on the dashboard. The data were used with a simplified version of **ThermoAnalytics**' RadTherm, software used for simulating heat transfer at surfaces, linked to a simplified version of **AVL**'s FIRE, a CFD program. A CAD model of cabin temperatures and airflow was developed. RadTherm determined the A/C cooling needed to achieve equal cool down in 30 minutes with the thermal loads in the special STS and the control (standard) vehicle was 2.8 vs. 4.0 kW, a 30% reduction.

A vehicle simulator, using the **EPA** fuel economy numbers for the STS (16 mpg city/24 mpg highway) and the U.S. federal drive cycle, assessed the impact on fuel economy based on that load reduction, for 12,000 mi (19,310 km) of annual travel and A/C in operation 32.6% of the time. The percentage of vehicle operating time with A/C on was derived from an NREL study presented in 2004 and includes demisting time.

The simulator results over the test cycle were 18.5 mpg for the STS with no A/C operation, 15.4 mpg for both the standard STS with 32.6% A/C-on time, and 16.1 mpg for an STS with a 30% reduction in A/C cooling load. The standard STS would use 42.6 gal (161 L) of fuel per year just to power the A/C, whereas an STS A/C system that provided only 70% of the cooling would use 31.4 gal (119 L), a saving of 11.2 gal (42 L) or about 26%. The savings are not linear because the effect on fuel economy in demist is much lower.

Paul Weissler