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Development of the 100 MPG Bright Automotive™ Plug-In Hybrid Vehicle

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Abstract

The automotive industry is in a state of crisis due to global financial turmoil, volatile fuel prices and inefficient and outdated product designs. Formed in January of 2008 from a world-class team of automotive experts, Bright Automotive™ has developed a purpose-built, lightweight and aerodynamic plug-in hybrid for a specific market segment, to be unveiled at EVS-24, named the IDEA. Starting production in 2012, the Bright Automotive IDEA will meet the unique requirements of its target segment while delivering gasoline consumption of only one half gallon on a typical 50-mile day – a breakthrough, environmental, security and economical solution for the world.

The IDEA is the product of Bright Automotive's "whole system design" strategy, whereby multiple aspects of the vehicle are explored on a clean sheet of paper and synergies are developed to build a stronger overall value proposition. For example, its lightweight, aerodynamic, aluminium and composite structure enables the vehicle to benefit from a lighter, lower-cost battery and electric drive. The IDEA's parallel, road-coupled hybrid drive system leverages common engine and transmission components and electric rear axle, resulting in lower engineering development costs than for highly integrated hybrid systems. The IDEA also provides the benefit of all-wheel-drive for inclement weather and improved safety. Focused user groups from Bright Automotive's target market have provided hundreds of hours of input into the design process to help optimize the vehicle to meet specific and mission-critical needs.

This research work summarizes development of the vehicle, with particular emphasis on fuel consumption and its performance. It also discusses Smart Grid compatibility, cost of ownership, and illustrative key innovations that are combined in the novel product with the potential to bring dramatic fuel efficiency to mass markets.

Keywords: cost, efficiency, electric drive, emissions, fleet, parallel HEV, PHEV, thermal management, V2G

1 Introduction

In 2006, Rocky Mountain Institute (RMI) initiated a study to design a plug-in hybrid vehicle as a replacement for the current US Postal Service (carrier route) vehicle [1]. The study was initially sponsored by the Rose Family and Thornton Foundations and was completed in October 2006. Following this effort and a significant exploration in Smart Grid technology and implementation, RMI led a consortium of interested parties to develop a plug-in hybrid utility vehicle concept capable of rapid, large-scale implementation for prompt national reduction of oil use and emissions. Members of the consortium included Alcoa, Google.org, Johnson Controls and The Turner Foundation. This effort culminated in a major design collaboration of vehicle subject matter experts and confirmed a fundamental design concept that would become the basis of Bright Automotive, Inc, spun off in January 2008.

2 Bright Automotive Hypothesis

A purpose-built, lightweight, aerodynamic plug-in hybrid will achieve superior commercial viability, especially in the commercial van market where annual fuel expenditures have become unacceptably high in recent years.

3 Plug-In Hybrid Design

The Bright Automotive plug-in hybrid was designed following the RMI "whole system engineering" philosophy with a conscious effort to include multiple options in the "clean sheet" analysis that produced the final design. A significant endeavour to exploit synergies within the solution set is a fundamental goal in this philosophy. A plug-in hybrid is an intelligent compromise between a conventional "full hybrid" and a "pure electric vehicle (EV)". The strength of a plug-in hybrid is its ability to leverage efficient and renewable energy from the electrical grid while reducing the expensive battery component to deliver a practical solution for rapid implementation.

Conversely, EV designers must size the battery to meet a reasonable distribution of daily travel, usually in excess of 160 km per day. If sized too small, reduced utility and "range anxiety" results. This is the condition EV drivers feel when they are critically concerned about their vehicle's ability to complete a mission due to low charge-state of the battery. The result is that EVs are still an expensive solution in most applications due to battery costs in excess of $20,000.

Plug-in hybrid electric vehicle (PHEV) designers have liberty to size the battery system for optimal utility and cost of ownership. The size of a pack can be optimized by studying the daily travel distribution of the target market and sizing below the "knee" in the cumulative distribution curve [2]. In this way, the PHEV makes effective use of the expensive battery system while leveraging the IC engine to provide energy for variable, longer-distance daily trips.

3.1 Vehicle Attributes

The cornerstones of the Bright Automotive plug-in hybrid are its purpose-built design (Figure 1) and its road-coupled, plug-in hybrid system. To keep hybrid system costs at marketable levels, the team selected and designed to aggressive vehicle mass [3] and aerodynamic targets. Although the vehicle is a member of a class that is traditionally large and heavy (segment average is 2440 kg), the Bright Automotive mass target was lower than that of Toyota Prius at 1250 kg. Early in the development process, it was determined that aggressive mass reduction is possible through the implementation of a mostly aluminium structure with key composite parts [4]. The added expense of the advanced structure materials was offset by the savings on fuel and hybrid propulsion system costs, primarily driven by a smaller battery requirement [5].

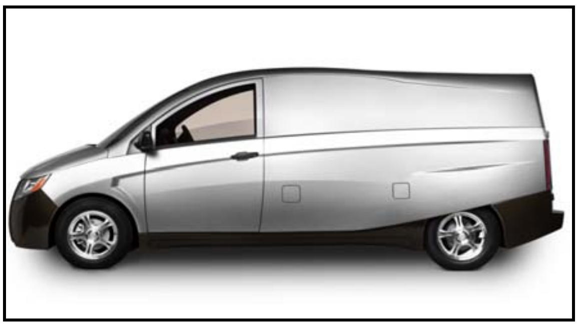

Figure 1: Bright Automotive IDEA vehicle

Aerodynamic loads are notoriously high – a source of poor highway fuel economy for this market segment. A common misconception is that aerodynamics are not important when considering an urban-dominant vehicle. In reality, this aspect remains crucial in order to reach overall fuel economy targets. Vehicle engineers must strive for balance in design to satisfy broad markets. Therefore, Bright Automotive set out to achieve an aggressive drag coefficient of three-fourths the norm for the segment (Figure 2). Bright Automotive enlisted the expertise of a premier aerodynamic engineering partner, with long-term aerospace background and tools [6]. The resulting design reduced overall drag area by some 30% against the segment.

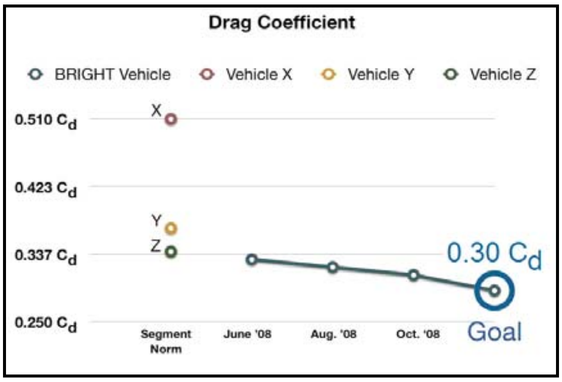

Figure 2: Aerodynamic Development Results

The original design of the Bright Automotive vehicle body (C_d = 0.332) was improved with a number of aerodynamic revisions: A-pillar protrusion reduced, windshield curvature increased, nose contour rounded, underside panels added for smooth underflow, boat tail reducing base area, and roof contour raising base area pressure. After this series of improvements were implemented in the model, a C_d of 0.313 was achieved. A further series of improvements is planned to reduce Cd to the target of 0.30.

Bright Automotive's aerodynamics development philosophy relies on proprietary Computational Fluid Dynamics (CFD) modelling (not commercial code), correlating and confirming results with accurate coast-down testing under carefully controlled conditions. Bright Automotive views aerodynamics as one of the most crucial areas to challenge the status quo, particularly in this large class of vehicle.

Plug-in vehicles operate on battery energy during short daily travel and use internal combustion engine power for long-distance operation. Bright Automotive research determined that in most cases, long-distance operation involves highway mode driving and can be accomplished most efficiently by a properly designed parallel hybrid [7]. Bright Automotive employs road-coupled parallel hybrid architecture (Figure 3) in order to maximize overall efficiency, performance, and keep hybrid system costs on budget. This allows both the front-drive engine and the rear electric axle to operate in harmony to deliver all-wheel-drive when needed, a feature with considerable commercial value, highly sought-after in cold climates and mountainous regions. During normal braking events, the electric drive system recovers kinetic energy to improve fuel economy. This energy is transferred to the energy storage device. A lithium battery pack is shown in a central location within the frame in figure 3.

Choice of front engine location was a compromise to enable a standard engine and transmission to package without intruding on the cargo area. While regenerative braking is biased to the rear under light to moderate deceleration in this configuration, it remains efficient for most driving styles and cycles. Under the less frequent aggressive braking conditions, regenerative brakes are overridden in favour of friction brakes.

An additional benefit of the parallel architecture is that engine operation is a strong function of accelerator pedal position in addition to battery state of charge. Therefore engine noise is much more consistent with vehicle operation (serial hybrids may operate the engine at relatively high output even during very low speed and stopped conditions). Because the engine operation is responsive to vehicle driving conditions, emissions control is more challenging for the chosen architecture. Bright Automotive is implementing a range of emissions control strategies to ensure that the vehicle meets certification requirements.

Emissions of carbon dioxide is an area where the IDEA vehicle performs particularly well against the competition. Bright calculates CO_2 using full-cycle figures of GREET 1.8, Argonne National Laboratory (11.16 kg/gallon gasoline). Electricity generation CO_2 is estimated from the gross US electric generation and carbon dioxide emissions figures of the US Energy Information Agency (605 g/kWh). The competitive vehicles generate on average 1000 g/mi (622 g/km) whereas the IDEA generates 270 g/mi (168 g/km), both in highly laden usage condition, 20K annual miles.

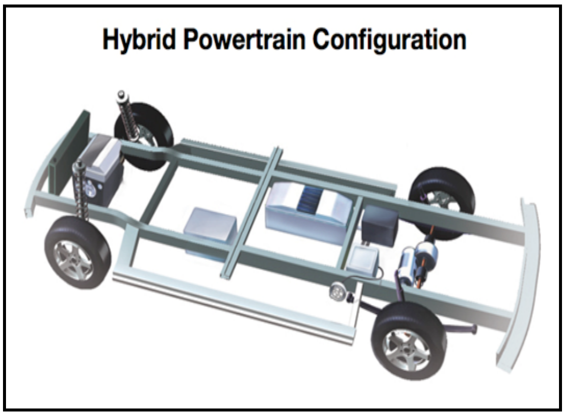

Figure 3: Parallel, Road-Coupled Architecture

The most striking benefit of parallel architecture is the cost savings associated with smaller propulsion components like the electric drive system. With a serial hybrid, the cost of motor and generator are substantially higher because they must be rated for greater duty (see Table 1). The battery size is also larger to accommodate a slightly lower steady-state power-path efficiency of the serial hybrid. The combined mass savings of the parallel architecture is estimated at more than 100 kg versus a serial configuration. Further rationale for the road-coupled approach derives from the robust dependability of redundant power paths. Each system can operate independently in the case that the other is in a fault mode. Naturally, performance is reduced under this condition, but it provides confidence for commercial operators knowing that they have this capability.

Table 1: PHEV Cargo Van Drive System Comparison

	If Parallel	If Serial
Drive Motor [max kW]	50	130
Battery Pack [kWh]	10	11
Generator [kW, cont]	4	50
Transmission	AMT	n/a
Engine [kW, peak]	80	90

Regarding engineering development costs, the IDEA powertrain employs custom software for controlling the system, but the components are readily available within the automotive industry. This solution keeps hybrid system development costs at a minimum. Fully integrated systems can be prohibitively expensive to develop as demonstrated by the estimated billion-dollar cost associated with major hybrid programs [8].

3.2 Analyzing Vehicle Performance

Road-coupled hybrid configuration also enables full power and torque transmittal from both electric and gasoline power plants. Other configurations either neglect this capability completely or can only provide a fraction of their total power [9]. The vehicle's acceleration is better than the segment norm, estimated at less than 8 seconds for 0 - 100 kph. The electric drive system produces 1600 Nm at the rear axle, approximately 4800 N of peak thrust. In addition, the front IC engine produces approximately 170 Nm of torque, translating to 2000 Nm in first gear at the wheels or about 6000 N thrust. Combined, during an aggressive pedal input, the powertrain produces up to 11 kN of thrust, accelerating the vehicle at up to 0.7g. For comparison, a heavier, V8-powered full-size van achieves about 14 kN thrust, with maximum acceleration of about 0.6g. Lightweight design and platform structures have also enhanced vehicle handling.

3.3 Fuel Economy

Plug-in hybrid architecture allows the vehicle to operate mostly on stored electrical energy during the initial 30 miles of operation. Typical daily travel of 50 miles results in only 20 miles, or 40%, gasoline-derived travel. Bright Automotive's selected market and vehicle, being an urban travel dominated segment, is designed to achieve 40 mpg (5.9 L/100km) during this 40% of travel that the engine is consuming fuel. Thus, the effective gasoline usage during typical operation is similar to achieving 100 mpg (2.4 L/100km) with a standard vehicle (Figure 4). While some electricity is also consumed, the cost of this energy is stable and roughly one dollar per day. Furthermore, the advent of renewable energy portfolio standards and similar global initiatives is expected to bring more clean power to the utility grid as time progresses, with a natural synergy of wind-generated electricity at night being usable at variable rates by a fleet of plugged-in hybrid and electric vehicles [10].

Factors that contribute to dramatically low gasoline consumption for 50 mile daily travel include the following:

1. 30 of first 50 miles are “engine-free”
2. Target market segment is significantly urban-driving biased, favourable to HEV
3. Drag area, C_dA, is ~30% less than class-average
4. Mass is ~36% less than class average
5. Hybrid system controls engine to operate along high-efficiency path
6. Hybrid system avoids excess engine idling
7. Hybrid system sources electric drive for light-duty loads
8. Electric drivesystem heat is recovered to pre-heat engine
9. Design uses low rolling-resistance tires

Vehicle dynamometer and road testing is confirming simulation studies that show dramatic reductions in fuel consumption compared with the segment (average is 10 to 14 mpg or 23.5 to 16.8 L/100km in urban driving, depending on payload). A heavily laden IDEA vehicle is projected to achieve 58 mpg (4.1 L/100km, gasoline consumption only) in urban-dominated (80% FTP schedule) driving for a 67 mile daily route. A nominally-laden IDEA consumes gasoline at an effective rate of 100 mpg (2.4 L/100km) for the standard 50 mile daily drive schedule.

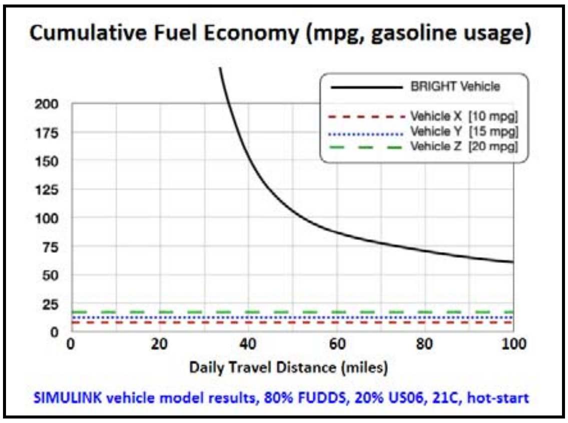

Figure 4: Fuel Economy Comparison

3.4 Determining Cost of Ownership

Bright Automotive has selected a unique market path to reach high volume production with plug-in hybrids. Bright Automotive’s chosen market segment is one that historically represents over 400,000 US vehicles annually and is under extreme duress due to escalating and volatile fuel prices. Demand in the segment has fallen by over 75,000 units, even prior to the global financial concerns of September, 2008. Fuel economy represents a serious concern among this buying group. Volatility of fuel prices makes buyers wary of the potential for price increases in the future, leading them to seek ultra-low consumption options like the IDEA [11]. Bright Automotive has received significant pre-production sales interest by offering a solution that provides a lower Total Cost of Ownership (TCO) to the market (Figure 5).

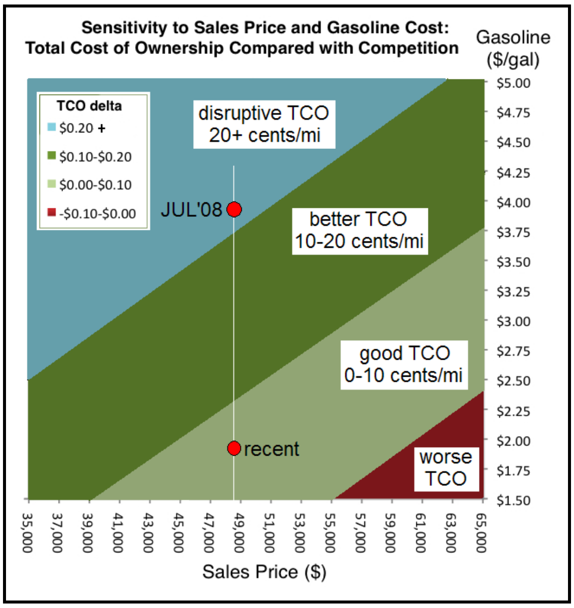

Figure 5: TCO as sales price and fuel cost

The Bright Automotive TCO analysis includes fuel cost, depreciation, depreciation write-off, fees, taxes, battery tax credit, finance costs, insurance, maintenance, and repairs. Fuel costs can vary widely over time, so Bright Automotive illustrates the TCO as a function of gasoline price and vehicle sales price. Most components of ownership cost, like insurance, financing, taxes and fees, are comparable to current market solutions. However, energy costs are much lower for the Bright Automotive vehicle, and depreciation is higher for some years, due to the higher costs of the PHEV system.

Bright Automotive uses a depreciation schedule that is similar to the Toyota Prius. Both vehicles possess uniqueness in the market segment of iconic, extreme efficiency hybrids, but the Bright Automotive vehicle will serve a different segment. Figure 5 compares the Bright Automotive TCO to full-sized vans in the US market. Vehicles are compared in a common, high-laden condition using 20,000 annual miles. The red region represents a negative value, whereby the benchmark vans have a better TCO. Green and blue regions represent superior TCO regions. As shown, fuel prices of summer 2008 created a highly positive TCO condition for the IDEA.

4 Smart Grid Interface

Smart Grid is a vital technology in the future of electric utilities. The technology encompasses a range of initiatives like smart meters and enables increased effectiveness and efficiency in generating and transmitting electric power (Figure 6). The Bright Automotive plug-in hybrid is being developed in close collaboration with Duke Energy [12] and other leading utilities with a mandate of making the interface directly compatible and capable of optimizing charging rate and duration in response to variable grid conditions and communications.

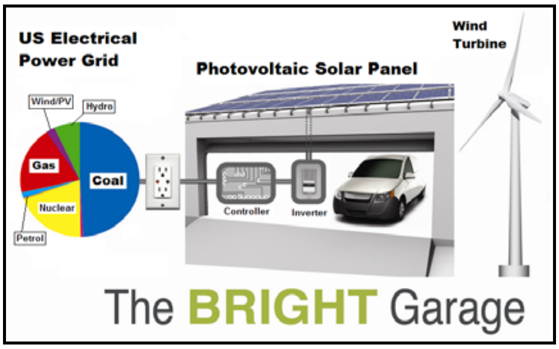

Figure 6: Elements of the Future "Smart Grid"

4.1 Smart Grid Performance Targets

Smart Grid is an initiative that combines solar capacity, smart meters and storage batteries along with other generation and transmission devices to save energy and improve service reliability. The program's goal is to reduce residential electricity consumption and improve its reliability by refining and controlling the use of power. It also will help utilities determine how to integrate small solar generators and energy-storage technologies to reduce peak demand and improve reliability. The first step in implementation is to be able to control the charge rate of a PHEV in response to real-time price signals or other controls coming from the utility using a standard communication method.

4.2 Smart Grid System Benefits

Utilities are working to learn more about how to use batteries from plug-in electric vehicles as a source of stored energy. That could ease peak-time energy demand and reduce the need for peak generating plants. The program will demonstrate ways that utilities can improve the efficiency of their grid operations, losing less energy before power gets to home meters. Interactive smart meters are a key starting point in order to demonstrate Smart grid capability. Those meters give the customer and the utility substantial information about how energy is used after it goes through the meter. And it allows for a more finely tuned control of energy use [13].

5 Vehicle Innovations

A core value of Bright Automotive is to innovate throughout the product development process. The first innovation discussed here is the IDEA's patent-pending mobile office environment. Numerous customer interviews were conducted to evaluate the need for high-productivity workspace within the cab of a commercial vehicle (Figure 7). Bright Automotive considered several approaches that would provide a safe system for both driver and occupant.

Secondarily, Bright Automotive focused on a breakthrough level of convenience for commercial operators requiring an improved environment for completing mission-critical administrative and logistics tasks. The resulting solution provides a comfortable passenger seat that is capable of transforming into a safe and substantially functional work desk with room for the operator to pivot, placing legs directly underneath the working surface in a standard seat and desk arrangement.

Figure 7: Vehicle interior in normal configuration

Figure 8: Patent-pending office environment

Figure 8 shows a model of the office environment developed as a result of extensive customer research. The seat is shown in the desk-transformed orientation.

An additional innovation is in the category of hybrid vehicle thermal management. A key challenge in achieving superior fuel economy is winter or cold-climate operation of the internal combustion engine (engines are not efficient at low temperature). Bright Automotive's innovative solution is to recover heat, typically 1200 Wh, from the electric traction system during the initial period of charge-depleting operation (Figure 9). This is enough heat to raise engine metal temperature substantially, allowing the engine to reach an efficient operation condition early in the drive schedule, normally before its operation is required.

It is important to note that the heat used to pre-warm the engine would otherwise have been wasted. No additional fuel or electricity is used. Through synergistic design of the thermal system, the waste product of one component is carefully harnessed as a useful input to another.

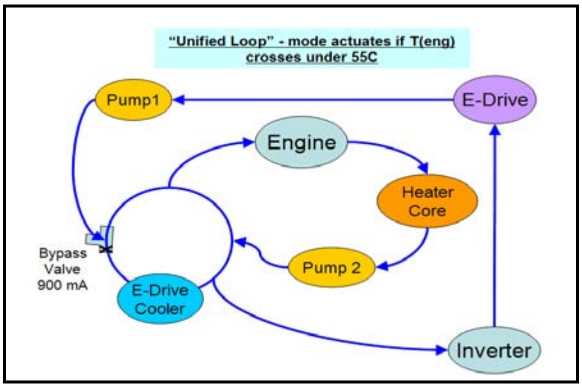

Figure 9: Electric drive system heat recovery

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Jeff Ronning, Hybrid Systems Architect, is a plug-in hybrid pioneer with early research through SAE and GM since 1995. A mechanical engineering graduate of Kansas State University, he devoted the 1990s to the EV_1 propulsion system at GM and has supported numerous hybrid vehicle programs, often in a capacity of thermal and energy management at Delphi. Joining RMI in 2006, Jeff developed propulsion system parameters and strategies for the Bright Automotive vehicle. Energy consumption modelling and the development of strategic technical solutions are Jeff's passions.

Amory Lovins, Chairman and Chief Scientist of RMI, has led global innovation for over three decades at the nexus of energy, resources, environment development and security. Educated at Harvard and Magdalen and Merton Colleges, Oxford, Lovins has received ten honorary doctorates, published 29 books, and advised governments and major firms worldwide on advanced energy and resource efficiency. *Car* magazine ranked him the twenty-second most powerful person in the global automotive industry. *Newsweek* has praised him as "one of the Western world's most influential energy thinkers".

Dr. J. P. Lyons is CTO of Novus Energy Partners and has 30 years' experience at GE Research. He was Chief Engineer for Electrical and Electronic Systems, serving as technology leader and mentor for a 250-member global team. A principal advocate of renewable energy within GE, he was the champion behind its 2002 entry into the wind energy business with record-breaking success. He recently led new GE business and technology initiatives on plug-in hybrid vehicles. Jim has served on the boards of Powerex and EDTA. Jim has a BSEE degree from Rensselaer Polytechnic Institute, an MSEE from Virginia Polytechnic Institute, and a Ph.D. from Cornell University.

John E. Waters, CEO of Bright Automotive, Inc., brings over 25 years of entrepreneurialism, engineering experience, and advanced automotive expertise to Bright Automotive. A pioneer in electric vehicles, John invented the battery pack system for General Motors' first production electric vehicle, the EV_1, and subsequent electric and hybrid electric vehicles. He also advanced and commercialized enabling battery technologies, such as lead acid, nickel metal hydride, and lithium-ion for transportation solutions. John helped launch Delphi Corporation's lithium battery business, and led the joint venture of lithium battery manufacturer EnerDel and lead the transportation practice at Rocky Mountain Institute.

Dave Lauzun brings a wealth of automotive experience to Bright Automotive based on his experience in positions of Engineering Design, Program Management, Vehicle Development, and Quality. Dave devoted 24 years to Chrysler, where he most recently led the development of Chrysler's mid-size sedans. In previous positions at Chrysler, Dave served as Program Manager for sedans and Quality Manager for the Jeep Team. He also held leadership positions in several design groups and manufacturing facilities. Dave's formal training includes Master's Degrees from the MIT Leaders for Manufacturing Program.