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A COST EFFECTIVE ARCHITECTURE FOR A 3-WHEEL PLUG-IN HYBRID CITY VEHICLE (GOBO PLUG-IN HYBRID): PART 1 – DESIGN AND PERFORMANCE

Ketan Ranade and Hassan I. Mohamed Nour

Department of Electrical Engineering

California State University, Long Beach

1250 Bellflower Boulevard Long Beach, California 90840

E-mail: ketan_ranade@Toyota.com / nour@csulb.edu

Abstract: Recently, several automakers have introduced Plug-In Hybrid vehicles that have the ability to operate in all-electric mode. These models provide the ability to drive short distances (ranging from approximately 10 to 40 miles) in electric mode, without the operation of the onboard internal combustion engine (ICE). The ICE provides long range operation and charge sustaining capabilities. Since these models offer the ability to drive in electric mode as well as the ability to take longer trips with the ICE, their future sales success should be considered reasonably optimistic. The one hurdle that may prevent this type of vehicle from gaining widespread acceptance is the high price premium these models have over their conventional ICE powered counterparts. In this paper, a design for a practical and cost effective plug-in hybrid vehicle is presented. The 3-wheel plug-in architecture includes a 50-hp, 3-phase ac induction motor driving the front two wheels and an independent small ICE directly powering the rear wheel. The battery pack is sized for an average daily commute without the need for the ICE. However, the on- board light-weight ICE provides for extended driving range when needed. A Prototype of this vehicle is built and currently being tested at the college of Engineering, California State University, Long Beach. An overview of the implemented cost-effective architecture is discussed and the lessons learned during the design and manufacturing stages are presented.

1. Introduction:

The overall concept of the 3-wheel plug-in hybrid is based on a two passenger city commute vehicle. The vehicle is powered by an electric motor ***or*** a gasoline engine (GOBO- Gas ***Or*** Battery Operated). The front two wheels are powered by a 50 hp AC induction motor that transfers power to the front two wheels via a single gear front-wheel drive transmission and differential. During the prototype stage a 10kw*hr sealed gel type lead acid battery pack is being used to power the electric drive system. Once the battery is depleted, the single rear wheel is powered by a 750cc motorcycle engine.

The powertrain arrangement for the 3-wheel plug-in hybrid was inspired by AC Propulsion's "Long Ranger" Trailer that was developed to provide extended range capabilities for pure electric vehicles [1]. This trailer consisted of a 500cc fuel injected motorcycle engine coupled to a 20kw generator. The high output generator provided for enough power to maintain a constant state of charge in normal city and freeway driving conditions. Although this design provided for a practical means for extended range, the overall design was costly due to the 20kw generator and its supporting electronic charging hardware. As noted previously, in the GOBO plug-in hybrid, the engine power is transferred directly to the rear wheel instead of powering a generator thus reducing weight and cost.

The first section of the paper is concerned with presenting the cost effective architecture implemented and the second section gives a closer look into the design, manufacturing and testing of the prototype.

2. Cost Effective Architecture:

The cost effective architecture of the GOBO Plug-In hybrid is based on five key principal items:

- Power Electronics: Utilizing power electronics (electric motor and motor controller) from existing high volume applications
- Electric Motor Selection: Utilizing induction A/C motors instead of costly permanent magnet type
- Battery Sizing: Limit size of battery to ~ 10 kw*hr (just enough for a daily commute of ~ 30 miles) since range extending ICE is on board
- Mechanical Parts: Vehicle component sharing (steering system, brake system, axles, wheels) etc. with mass produced models
- Less Wheels and Seats: Consider 2 seat / 3 wheel design. Less seats and one less wheel / suspension system equals less costly design for commuting purposes

These items are presented below in further detail.

Power Electronics:

Currently the Material Handling Industry in the U.S. is one of the most profitable businesses selling and servicing electric vehicles. Thousands of electric forklifts , tow tuggers and narrow aisle stand up trucks are sold each year by 6 major brands (Hyster, Yale, Crown, Toyota, Raymond and Linde) [2]. For this industry, power electronic suppliers have developed cost effective hardware that provides for high reliability. Cost has been reduced primarily due to the automation developed to support the high volume production of these components. For years this industry used DC motors and controllers. Now the majority of the manufacturers offer AC drive systems, which provide greater efficiency and require less maintenance due to their brushless motor designs. Recently all of the major industrial equipment manufacturers have increased the bus voltage of their drive systems from 48 volts to 80 volts. The voltage operating range is expected to continue to increase for greater efficiency.

The motor controller utilized in the GOBO plug-in hybrid is currently being used in the Material Handling Industry. It provides for adequate power performance (both drive and regeneration modes) and high efficiency. Since this controller is mass produced, the cost is relatively low.

Electric Motor Selection:

Although DC brushless motors, in most cases, offer slightly greater efficiency (by ~ 2-3 percent) and better power density vs. induction type motors, the price and availability of the rare earth elements needed, in this case Neodymium, should be considered.

Rare earth metals are found in relatively small quantities and are usually mixed in with other minerals. Neodymium, the rare earth element used to produce magnets for brushless DC motors is difficult to mine and process safely. Currently China is the only country in the world mining Neodymium on a large scale. In fact over 95% of the world's Neodymium production is from China [3]. Increased "in country" demand and tougher environmental standards has caused China to limit the export of Neodymium over the last 5 years. Therefore, the price of this rare earth element has increased by nearly 150% (from ~$20/kg in 2005 to over $50/kg in 2011) in this time frame. Since Neodymium is used in everything from personal electronics to wind turbines and electric motors, worldwide demand is expected to continue to rise. This supply - demand issue may cause a further increase in price over the next 5 to 10 years.

Modern inverter controls allow improved performance of induction motors at all speeds. As the motor speed changes, the synchronous speed is continuously altered in order to achieve the desirable torque with lower levels of losses.

Induction motors offer many advantages including low cost, maintenance-fee operation and good performance with the use of smart inverters. This type of motor is therefore a good choice for economical electric vehicles.

Battery Sizing: Even though the price of advanced batteries (LiON) has come down slightly over the last 10 years (2000- 2010), the battery system remains the most expensive component of plug-in and pure electric vehicles.

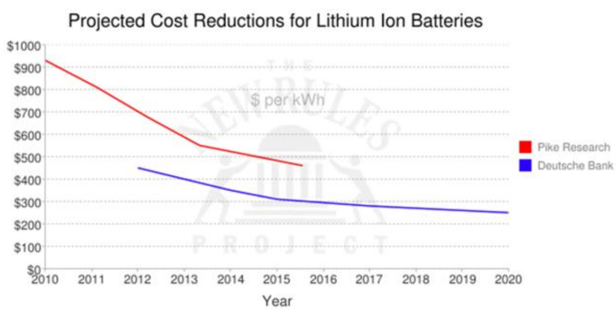


Figure 1 - Source: Pike Research

Currently the price of LiON batteries ranges from ~ $500 to $1,000 / kh*hr depending on the battery manufacturer and on additional hardware required for battery monitoring. Pure electric vehicles recently introduced into the market (Nissan Leaf, Tesla Roadster etc.) feature battery packs of approximately 35 to 40kw*hr. Even at an optimistic price estimate of $500 per kw*hr the battery cost for a pure EV is estimated to be ~ $18,000. This makes the battery cost of a pure electric car approximately 25% higher than a cost of an entire subcompact ICE powered vehicle (Nissan Versa, Toyota Yaris, Chevy Sonic etc.)

The GOBO Plug-in hybrid features a 10kw*hr battery pack, which provides an estimated range of 30 miles. Limiting the battery capacity to 10kw*hrs allows for decent range without a high cost penalty. Department of Energy data indicates that 89% of American's have a commute of 30 miles or less (see average daily commute chart - Figure 2). Therefore, for a vast number of Americans this type of vehicle will provide for an adequate means of commuting in pure electric mode.

A smaller battery also helps minimize weight which results in improved dynamics and improved overall efficiency.

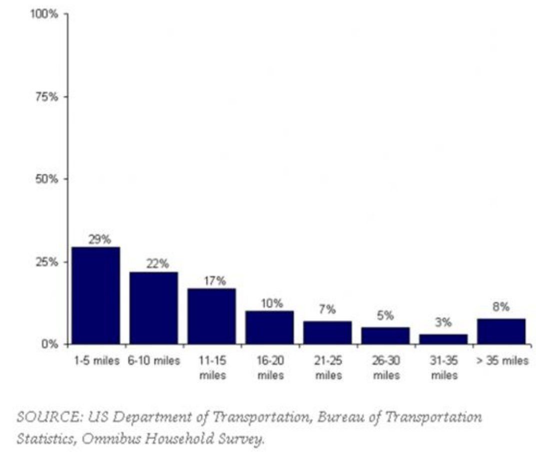


Figure 2 - Source: Department of Energy

Mechanical Parts: Component sharing with mass produced models is key to reducing overall cost. The largest automakers in the world (GM, Toyota, VW etc.) utilize this technique to drastically cut development cost for their new model introductions. For example, the VW Golf, Beetle, Jetta, Audi TT and Audi A4 are almost identical in overall architecture. These models share engines / transmissions, driveline components, brake systems, steering components and suspension hardware. Electronic hardware that supports fuel injection, vehicle stability control, HVAC and multimedia operations are also shared. These techniques help ensure low cost development and manufacturing.

These cost cutting techniques seems to be missing from many of the plug-in electric vehicles that have recently been launched. High development and manufacturing costs of individual components invariably leads to a high overall premium for the vehicle.

The GOBO plug-in vehicle uses off the shelf components from existing OE models. The suspension, transmission, brakes, steering etc are all proven carry over components from light / efficient front wheel drive on-road vehicles.

Utilizing these components has accelerated the development process and has helped keep the overall cost low.

Less Wheels and Seats: Vehicles with 3 Wheels have been part of the Automotive landscape since the very beginning. In fact, Karl Benz's first prototype often credited as the "world's first automobile" was a 3 wheel design (see Image 1).

Three wheel automobiles are inherently less costly to produce. Having one less wheel and therefore less components (springs, shocks, suspension linkages, brake components, wheel hubs, bearings etc.) can significantly cut the overall cost of a vehicle. In applications where power is delivered to the single wheel, a differential is not required, further reducing cost. 3-Wheel designs are also inherently lighter, thus requiring less power performance. Therefore, some cost reduction can be realized by downsized powertrains as well.

As mentioned earlier the GOBO plug-in hybrid is based on a small 2 seat commute vehicle. Recent U.S. Census data shows that over75% of Americans commute to work alone (see Figure 3).

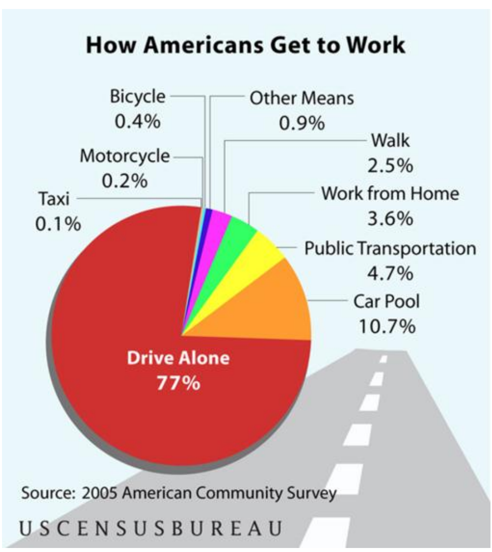


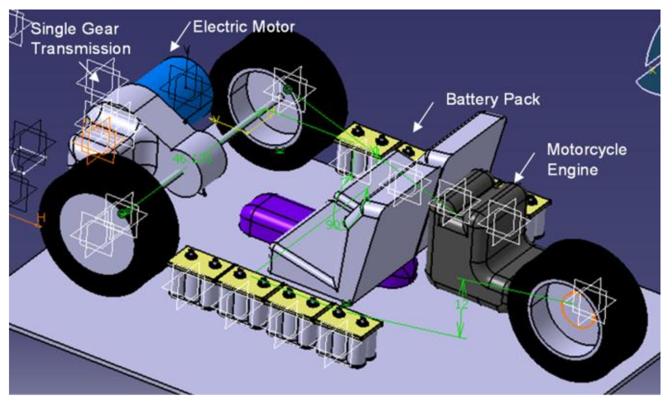
Figure 3 - Source: US Census Bureau

Therefore a 2 seat, low cost, environmentally friendly vehicle could meet the commuting needs for a large percentage of the U.S. workforce. Having 2 less seats plus less chassis structure to support the seats could result in significant cost savings as well.

Image 1: Karl Benz's first Motorwagen - Source: Google Images

3. Overall Design / Manufacturing / Lessons Learned

Overall Design: The illustration below defines the overall architecture of the GOBO plug-in hybrid vehicle. In the actual vehicle the battery pack is located in between the driver and passenger seats. See images on next page.



The vehicle is expected to weigh approximately 1,700 lbs with gel type sealed lead acid batteries and under 1,500 lbs with more advanced LiON batteries. Both the electric motor and motorcycle engine are sized to run the car individually at freeway speeds. The transmission is a traditional front wheel drive set-up with a total gear reduction of 8 to 1 (Final Drive = 4.25). Top Speed in electric or gas mode is expected to be ~ 65 mph. Electric Range is expected to be ~ 30 miles in city driving. Eventually, regenerative braking will be possible not only in EV mode but also when the vehicle is being driven with the ICE.

Overall Design Continued:

Key Specifications:

Total Weight	~ 1,700 lbs
Overall Length	152 in
Width	65 in
Height	47 in
Wheelbase	119 in
Max Power Rating of Electric Motor	50 horsepower
Max Torque Rating	90 ft*lbs
Max RPM	8,000
Single Gear Ratio (w/ Final Drive)	8 to 1
Front Wheel Dia	15 inch
Front Tire Dia	21 inch
Est Frontal Area	20 sq feet
Est Drag Cd	.25 (TBD)
Horsepower of Range Extending ICE	~ 100 hp

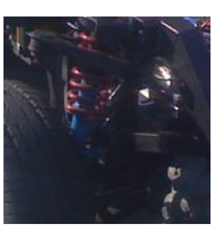
Fabrication / Components:

Chassis:

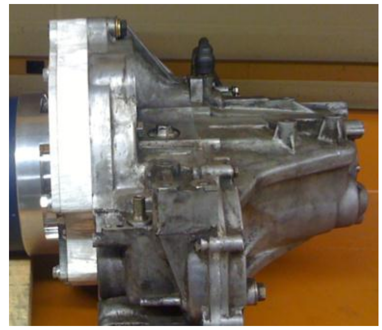
Thin wall rectangular Steel tube (most members= .060 inch) / Mig and Tig Welded

Suspension System -Front: Double Wishbone Independent with Coilover Shocks / Multiple Link Rear: Mono Coilover with Rear Swing Arm

Front: Rear:



Transaxle: Front Wheel Drive with Single Gear (8 to 1 gear ratio) with bell housing spacer and coupler



Steering: Rack and Pinion (Manual Type)

Brakes: Disk Brakes in Front with Electric Vacuum Pump Boost / Rear Disk with Manual Hand Brake

Motor: 3 phase induction motor (Max Power 50hp/ Max Torque 90ft*lbs / Max RPM 8,000)

Controller: Industrial Vehicle Type AC Controller / Designed for Forklift and Electric Tow Tugger applications / Air Cooled

Charger: Rated at 1 kw (110 or 220 v input) / Requires an overnight charge / Built in 30 amp DC to DC 12 volt converter

Batteries: DEKA Deep Cycle 100 amp*hr / 12 volt

ICE: Currently testing 600 cc and 750 cc fuel injected engines from Yamaha

Bellypan: Aluminum Sheet

Floorpan: Carbon Fiber

Seats: Sparco Bucket Seats (not racing type)

Seatbelts: Sparco 4 point Harness (not racing type)

Body: Fiberglass (under development)

Performance Characteristics: Since the GOBO prototype vehicle is not yet registered for street use, initial testing has been limited to the campus parking lots of Cal State Long Beach. Overall Performance is better than expected. Due to its low center of gravity, reverse trike format and long wheelbase the overall stability is good. The vehicle is easy to maneuver with safe and controllable under steer characteristics. Braking has been greatly improved by adding a 12 volt brake boost pump to the circuit. Power delivery in EV mode is precise and easy to control. Seating position is comfortable and visibility is excellent.

The 8 to 1 fixed gear ratio transmission provides for a good mix of acceleration performance and top speed.

Overall efficiency in pure electric mode has not been measured yet. However, due to its light weight design an overall efficiency of approximately 200 watt*hr/mile is expected in normal city driving conditions.

The 1 KW charger provides a complete charge in 6 to 8 hours.

Areas for Improvement:

- Further tuning of suspension spring rates in the front and rear is required
- Ground clearance could be an issue in some driving conditions (entering or leaving a sharp approach angle etc.)
- Steering rack with a more aggressive ratio should be considered for quicker response
- Diameter and bushings of front sway bar needs further tuning
- Regeneration is adequate but could be stronger / Ideally should be adjustable while driving
- Proper interface for energy usage / voltage / motor temperature etc needs to be developed
- Battery monitoring needs to be added
- An ICE with Fuel Injection is currently under study. Initial powertrain was carburetor type

Lessons Learned: This project has consumed more time than initially anticipated. Even though the overall design was well thought out prior to any fabrication, it still took countless man hours to get the first prototype running.

Summary and Conclusions:

- Cost cutting principals highlighted in this paper did help to keep cost under control and did speed up development of the prototype
- Adequate on road power performance can be achieved by utilizing power electronics from the Material Handling Equipment industry
- Three wheel dynamics are better than expected. The GOBO Plug-In feels confident and stable on the road. This level of good dynamics was not expected for the first prototype
- The cost of LiON technology is still prohibitive and therefore does not lend itself well for prototype vehicle testing
- Lead acid batteries are an inexpensive way to conduct prototype testing on new electric vehicle designs
- Even though rectangular tubing (easier to weld than round tubing) was utilized to manufacture the frame, cutting the steel pieces and welding the chassis was the most challenging part of the prototype built
- In a reverse trike format, chassis roll loads are taken up entirely by the front suspension mounts. These mounts have to be more robust than a traditional 4 wheel set-up
- A proper machine shop with a lathe, mill, metal bandsaw, bending tools, water jet cutting and good welding equipment is required to build a full scale prototype

Next Steps:

Once the aforementioned improvements are made, a body with headlamps, turn-signals, and mirrors will be developed. This will be necessary in order for the vehicle to be registered for on-road use. In the state of California, a 3 wheel vehicle (otherwise known as a Trike) is normally classified as a motorcycle.

Images:

Initial Concept Idea (collaboration with Pasadena Art Center):

Current Condition of Prototype (without Body):

References:

[1] Thomas B. Gage- A.C. Propulsion and Michael A. Bogdanoff – South Coast Air Quality Management District, *Low Emission Range Extender for Electric Vehicles,* August 1997

[2] Industrial Truck Association, *2011 United States Factory Shipment* (available at https://www.indtrk.org/marketing.asp)

[3] John D. Sutter- CNN, *The race to make the world's strongest magnet*, March 2011

Figure 1 – *Projected Cost of LiON Batteries*, Source: Pike Research

Figure 2 – *Average daily commute distance for Americans*, Source: U.S. Department of Energy

Figure 3 – *How Americans get to Work*, Source: U.S. Department of Transportation

About the Authors:

Ketan Ranade received his Bachelor's in Mechanical Engineering from the University of California, Davis in 1995. He is currently pursuing a Master's Degree in Electrical Engineering at California State University, Long Beach. He joined Toyota Motor Sales in 2001, where he currently holds a position of Senior Product Planner. His main interests are Power Electronics and Alternative Fuel Transportation.

Hassan I. Mohamed Nour received his Ph.D. degree from the University of Southern California (USC) in 1985. He was a research scientist from 1985-1988 with the Department of Electrical Engineering at USC. In 1988, he joined California State University, Long Beach (CSULB) where he currently holds the position of professor with the Department of Electrical Engineering. His research areas of interest include power system analysis, high-voltage insulation, energy conversion and smart grid applications. He is the winner of Distinguished Faculty Teaching Award (CSULB, 2004) and Outstanding Faculty Award (AESB – 1993, 1998 & 2002).