Capstone Hybrid Vehicle Experience

Overview

This paper provides a brief overview of Capstone Turbine Corporation's application of its microturbines in hybrid electric vehicles, or HEV's. The original production microturbine design was strongly influenced by the space and durability requirements of vehicle applications. While the majority of Capstone microturbines today are used in stationary power applications, the technology is well suited for HEV's, and the company is seeing increased interest for vehicles that could result in significant future growth. The market needs driving this increased interest include higher fuel efficiency, reduced greenhouse gas emissions, and more stringent criteria for pollutant emissions. Several example HEV applications are provided in this paper, along with a high performance concept vehicle that shows that driving performance does not need to be sacrificed to achieve all the benefits of a hybrid electric vehicle.

Capstone's Early Vehicle History

Capstone was originally founded as NoMac Energy Systems in 1988 by Robin Mackay and James Noe. The company's initial activities included technical and market analysis of how a small gas turbine could be used in a variety of applications, including hybrid electric vehicles. Ford Motor Company funded some of this early research work, as did NASA and the Gas Research Institute. In 1993, NOMAC was sold to Ben and Harold Rosen, with participation from venture capital companies Sevin Rosen Funds and Canaan Partners. The Rosen brothers' vision for this new company was, in fact, to develop a clean microturbine that could become part of a novel hybrid electric drive system for vehicles using a flywheel for temporary energy storage. Ben and Harold also founded a separate company, Rosen Motors, to develop the vehicle drive train and the flywheel energy storage system. NoMac was renamed Capstone Turbine Corporation by its new owners, with the mission to develop the clean microturbine that would be used in the Rosen Motors hybrid electric vehicle.

In January 1997, the first demonstration of the Rosen Motors hybrid using a Capstone microturbine was conducted at the Willow Springs racetrack near Edwards Air Force Base. The demonstration showcased a Saturn vehicle with a 24kW Capstone, as seen in the video below.

http://www.youtube.com/watch?v=xG66JQmdMv8

However, timing is everything. When Ben and Harold Rosen tried to interest the traditional auto manufacturers in using their revolutionary technologies, it was at a time when fuel prices were low, SUV's were the high-margin sellers, and there were no significant market drivers to strongly reduce emissions and increase efficiency. Rosen Motors ceased operations at the end of 1997 for commercial reasons, although they had overcome many technical challenges to integrate the Capstone microturbine into their novel drive system. Capstone continued development of its clean, efficient microturbines for other hybrid electric vehicle applications, and increased emphasis on stationary power applications. In June 2000, Capstone made its initial public offering, and raised $130 million. In the IPO Registration Statement, hybrid electric vehicle applications continued to be a market opportunity, with the focus shifted to transit buses which had begun field trials as early as 1999.

Hybrid Electric Drive Systems

Capstone microturbines are well suited for use in series hybrid electric drive systems, where a battery or other electrical energy storage system provides power to an electric motor that ultimately drives the wheels. The microturbine provides the average power to recharge the on-board energy storage system. This is essentially how the Rosen Motors hybrid described above operated, where the energy storage system was a flywheel.

Series hybrid electric drive systems with significant battery storage capacity are also called plug-in hybrid electric vehicles, or "PHEV's," because their batteries can be recharged by plugging them into an electric outlet when they are not being driven. Figure 1 shows how a PHEV works.

An electric motor drives the wheels through a traditional mechanical component such as a trans-axle. Power to drive the motor comes from a battery storage system through an electronic vehicle drive system that controls the speed and power levels of the motor. The battery storage system gets its energy from three places.

- First, the electric drive motor can act as a generator to take power from the wheels back to the battery – this is called regenerative braking, and is one reason why hybrid systems achieve such good efficiency.
- Second, the battery system can be recharged from an electric plug-in station – at home or at public recharging stations. Using energy from the electric utility grid can actually be less expensive than using energy from traditional fossil fuels.
- Third, the on-board microturbine can use diesel or other alternative fuels to generate electricity to recharge the batteries even while the vehicle is in use. This significantly increases the range that the vehicle can travel compared to only relying on the battery energy storage, and does so with ultra-low emissions and high efficiency.

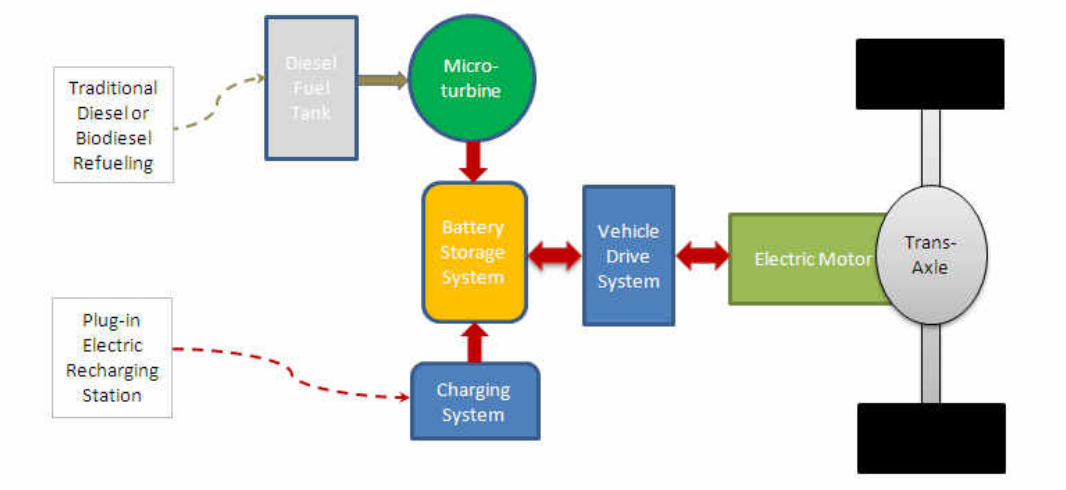

Figure 1 Schematic of a Plug-in Hybrid Electric Drive System

What's a Microturbine?

A microturbine is a small gas turbine, or miniature jet engine. Microturbines use a continuous shaft rotation to pull in air, compress it, add fuel for combustion, and use the resulting heated air to drive a turbine wheel. The turbine wheel provides the power to drive the compressor wheel as well as a generator mounted on the same rotating assembly. A recuperator (or air-to-air heat exchanger) is provided to extract energy from the exhaust stream and recycle it to preheat the incoming air to the combustion chamber. This greatly increases efficiency. Some characteristics unique to Capstone microturbines are:

- Air bearings are used to support the entire rotating assembly. No oil or other liquid lubricants are needed, so maintenance is extremely low with no hazardous materials to dispose of.
- The microturbine operates at very high speed – up to 96,000 rpm. So there is essentially no vibration, and components like the generator are smaller and lighter compared with traditional slower speed reciprocating engines.
- Since the combustion is continuous, it is well controlled with extremely low exhaust emissions. Capstone microturbines are able to meet the stringent California Air Resources Board requirements for heavy duty diesel engines without any exhaust aftertreatment.

Figure 2 is a cutaway view of a Capstone microturbine.

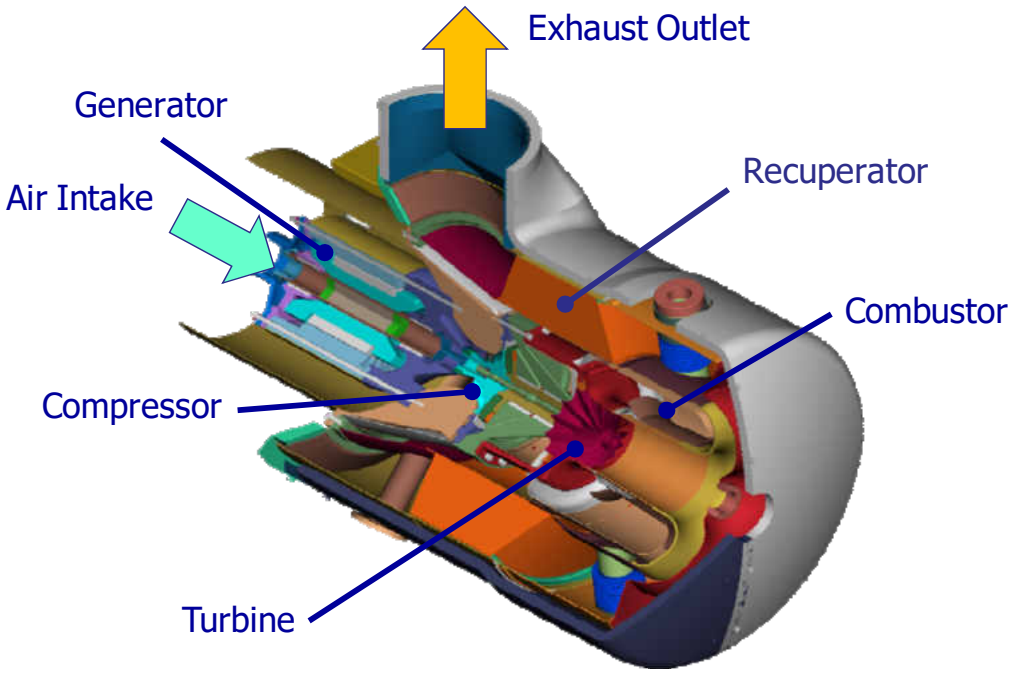

Figure 2 Cutaway View of a Capstone Microturbine Generator

Several hybrid electric drive examples are provided in the sections below to demonstrate the breadth of application that Capstone microturbines can serve.

Transit Bus Applications

Several bus manufacturers saw the opportunity to benefit from Capstone's clean, low maintenance technology, and began integrating microturbines into their electric drive systems. Transit buses are an ideal application for hybrid electric drives, since they require clean and quiet operation in densely populated areas with a stop-and-go drive cycle. In this case, the microturbine acts as an on-board battery charger (sometimes referred to as a "range extender") for what is otherwise a plug-in battery-powered electric vehicle. Figure 3 shows a schematic of what such a hybrid electric drive system looks like in a bus. Even though transit buses can weigh 30,000 pounds or more, the Capstone 30kW microturbine is suitable since it only needs to provide the average power required during daily operation. Figure 4 shows how the Capstone 30kW microturbine fits into such a series electric bus.

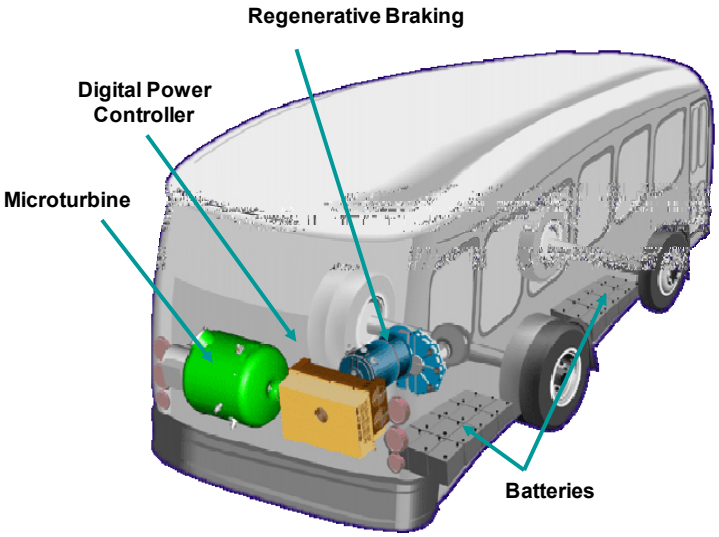

Figure 3 Series Hybrid Electric Drive System

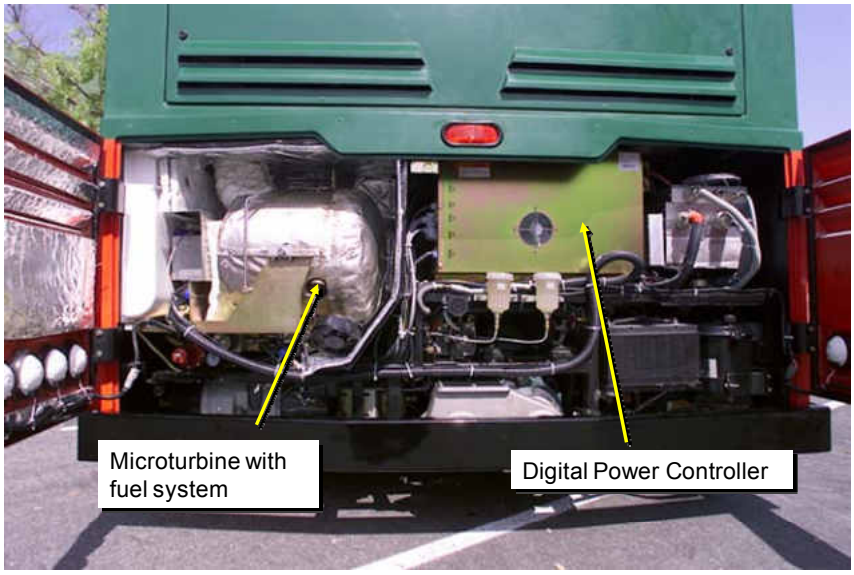

Figure 4 Capstone C30 Mounted in a Transit Bus

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As you might imagine, the transit bus market is extremely conservative. Therefore, any new technology or new bus manufacturer must prove themselves under real operating conditions before significant orders will result. Several manufacturers have perfected their applications and been able to penetrate this conservative market using Capstone microturbines coupled with their novel bus designs. Two examples are described below. Both companies have worked with Capstone since it went public in 2000, which shows the level of commitment and staying power needed to survive in this transportation sector.

DesignLine

DesignLine had the vision to develop a unique transit bus with better visibility, easier passenger ingress/egress, and more efficient operation than traditional buses. Figure 5 shows an example of their bus. These buses are located in New Zealand, where the company was founded. The photo shows the sleek modern design with excellent driver visibility and low floor access for passengers. The buses are 34 feet long (10.5 meters) with gross vehicle weight rating of 38,000 pounds (17,200 kg).

Figure 5 DesignLine Buses in New Zealand

DesignLine has been successful at gaining transit authority acceptance in many cities around the world, including Tokyo and New York City – two of the most demanding cities in the world. For example, to achieve a 90-unit initial order with New York Metropolitan Transit Authority, DesignLine first had to provide a Capstone-powered bus for a lengthy in-service trial using an existing city route. NYMTA measured economy, reliability, and surveyed ridership as part of this qualification. The DesignLine bus passed with flying colors, demonstrating more than 50 percent fuel savings compared to NYC's standard diesel bus fleet and higher reliability than their existing hybrid bus fleet. Ridership surveys did surface one potential issue, however – the buses were "too quiet." That's one advantage of Capstone microturbines – they have none of the traditional diesel engine vibration that can be felt inside the bus, and the whir of the turbine is easily attenuated so riders can hardly hear it. In fact, the air conditioning system in the bus is the loudest sound riders hear; except of course any outside traffic noise. Figure 6 shows the DesignLine bus during its trial route on 42nd Street in New York City.

Figure 6 DesignLine Bus (foreground) during Trial Operation in New York City

As a result of this, and other similar successful evaluations by major city transit systems, DesignLine now has received orders for 458 hybrid and alternative fuel buses. Capstone is a major contributor to that success.

EcoPower Technology (EPT)

EcoPower Technology is an Italian company that specializes in eco-friendly transportation, including transit buses. Figure 7 shows one of their hybrid electric buses with a 30kW Capstone microturbine during performance evaluation in Paris. EPT buses are smaller than the DesignLine models described above, with lengths of about 26 feet (8 meters). Buses currently operate in several cities in Italy.

Figure 7 EcoPower Technology Bus Operating in Paris

Some Unique HEV Applications

Several companies have taken advantage of the unique characteristics of the Capstone microturbine for specialty applications. Two are noted below to highlight Capstone microturbine benefits.

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Tomoe Mine Railcar

Mines have unique safety and environmental needs. Exhaust emissions can create health hazards in confined areas, so an extremely clean combustion system like the Capstone microturbines' is valued. For a portion of the railcar's operation, the microturbine is even turned off to assure no spark or exhaust emission can cause other safety problems. Several 30kW Capstone microturbines have been installed in these mining applications by Tomoe (a Japanese company), and demonstrate the benefits of clean, reliable microturbine power.

Figure 8 Tomoe Mining Railcar in Japan

"Spinner" Unmanned Military Vehicle

Another unique application that used Capstone microturbines was a prototype military vehicle that was to be an unmanned electric hybrid with the ability to completely flip upside down and still operate (thus the nickname the "Spinner"). Traditional reciprocating engines could not be used in this vehicle because their oil sump would not operate correctly if it was turned upside down. However, the Capstone C30 was perfect for this application, as its air bearings are not dependent on orientation. Figure 9 shows what this one-of-a-kind demonstration vehicle looked like.

Figure 9 "Spinner" Unmanned Military Prototype using Capstone C30

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Automotive Applications

Recently, Capstone has seen increased interest in using its microturbines for passenger vehicles. Several examples are described below.

"Whisper" Eco-Logic Hybrid SUV

Langford Performance Engineering in the UK received a government grant to develop a small hybrid electric passenger vehicle using the Capstone 30kW microturbine. They chose the Ford S-Max people carrier as the basic vehicle platform. Langford was able to pack a Capstone C30 under the hood, and integrate it with the rest of the electric drive system without reducing the car's seating capacity. Figure 10 shows the "Whisper" Eco-Logic Concept vehicle; named for its quiet and eco-friendly characteristics. Batteries are sized for a 40-mile range before the microturbine is started to recharge them. Fuel economy has been measured at 80 miles per gallon – much better than current production hybrids. The "Whisper" is registered and operating on public roads in the UK. Langford is now pursuing interest from major automobile manufacturers.

Figure 10 Langford "Whisper" Eco-Logic Concept Ford Hybrid

Capstone CMT-380 Microturbine Supercar Concept Vehicle

One of Capstone's customers also has integrated a Capstone C30 into a performance hybrid electric vehicle. This has captured the imagination of many, since typically hybrid vehicles are associated with high fuel efficiency and reduced emissions benefits -- not supercar performance. But the CMT-380 Microturbine Supercar has it all. Table 1 summarizes the estimated performance.

Table 1 Estimated Performance	
0-60 mph	3.9 seconds
Battery-Only Range	80 miles
Total Range	500 miles
Fuel Economy	75 mpg Average[(1)]
	210 mpg EPA[(2)]

(1) Using 50% Highway Charge Sustaining plus 50% City Charge Depleting Operating Modes

(2) Using proposed SAE J1711 method with .82 Utility Factor

Figure 11 shows a photo of the car partially disassembled so the microturbine is visible. Figure 12 shows what a completed performance hybrid will look like.

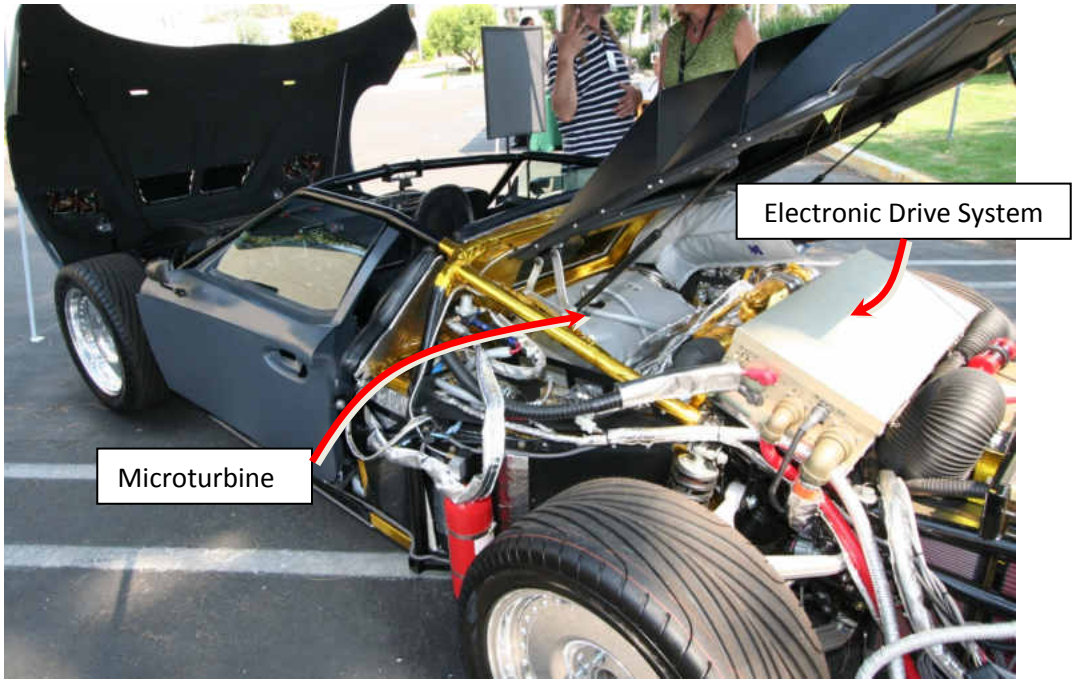

Figure 11 CMT-380 Microturbine Supercar Concept Vehicle with 30kW Microturbine

This performance hybrid uses high energy density lithium-polymer batteries with an expected range of 80 miles. Energy from the batteries is supplemented by a 30kW microturbine operating on diesel or biodiesel fuel, with enough fuel storage to extend the vehicle range to an estimated 500 miles. The CMT-380 MicroTurbine Supercar will be on display at the LA Auto Show in December 2009.

Figure 12 Finished Exterior of CMT-380 Concept Supercar

Conclusions

Capstone continues to see market growth opportunities for its clean and efficient microturbines in many applications, including as a range extender for hybrid electric vehicles. Microturbines have proven themselves in real operating situations, and have many valuable features, including:

- Ultra-low Exhaust Emissions
- High Efficiency – Low Greenhouse Gas Emissions
- Use of Alternative/Renewable Fuels
- High Reliability/High Durability
- Low Weight
- Essentially No Vibration
- Quite Operation
- Extremely Low Maintenance

Current production volumes are relatively low, so today's microturbine costs are higher than the millions of traditional reciprocating engines manufactured every year. However, Capstone is evaluating opportunities to optimize its products for the vehicle market, which will result in lower costs that could lead to high market adoption. The timing is right for clean US technology to help solve our energy and environmental problems, and Capstone is ready for the challenge.

