



**ETEC-Roush Hydrogen ICE Silverado Truck**



phone 602.716.9576

430 S 2<sup>nd</sup> Avenue Phoenix Arizona 85003

fax 602.256.2606

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## **ETEC-Roush HICE Silverado Truck**

Electric Transportation Engineering Corporation (ETEC), with technical support from our project partners Roush Industries and Powertech Labs have developed the HICE Chevrolet Silverado/GMC Sierra 1500HD 6 passenger 100% Hydrogen Internal Combustion Engine Truck (“HICE Silverado”).

The HICE Silverado is an OEM-quality conversion of the 1500HD vehicle platform utilizing the Vortec 6.0 Liter V8 engine. For this development effort, ETEC partnered with other experts in the automotive and gas systems field. Roush Industries is a major automotive engineering and low-volume manufacturing company that services automotive OEM’s and Tier One Suppliers in all areas of automotive engineering, development and testing. Powertech Labs is a wholly owned subsidiary of BC Hydro operating 18 Labs at its Surrey BC facility with approximately 80 professional engineers, scientists and technologists and is world-renowned in hydrogen storage component and systems design, testing and certification. With the expertise of ETEC, Roush and Powertech, the HICE Silverado is built to the latest standards (both established CNG standards and those in draft form for hydrogen) and to the highest quality.

Although HICE technology is not considered as technically advanced as fuel cells by some, a significant amount of research and development effort was required to achieve the desired performance and tailpipe emissions goals. Integration with the existing GM platform includes replacement of the original GM Powertrain Control Module (PCM) to provide the flexibility required for proper engine calibration, instrumentation and vehicle systems operation and control for the automatic transmission to properly operate with the power curve of the HICE engine.

Of the first 9 HICE Silverados in production, eight will participate in the “Integrated Wasted Hydrogen Utilization Project (IWHUP)” a 3-year, 18 million dollar (Cdn) initiative sponsored by several departments of the provincial and Canadian federal government. The ninth truck will participate in the DOE Advanced Vehicle Testing Activity (AVTA) under the FreedomCAR and Vehicle Technologies Program which will perform vehicle durability and performance tests and publish the results on the AVTA website.

The HICE Silverado has excellent performance and versatility with 195 Hp / 265ft.lbs of torque, 6-passenger capability and a range of 210 miles (EPA Highway driving schedule).

Although more advancements and refinements are always desired, the performance and emission results of the current HICE Silverado are very encouraging. Delivery of the first few HICE Silverados has begun and customer feedback has been extremely positive.



## HICE Silverado Development Background

Development of the HICE Silverado can be broken down into the following major development categories:

- ✓ Mechanical engine modifications
- ✓ Engine control hardware and software integration
- ✓ HICE Silverado fuel system integration
- ✓ HICE Silverado engine and transmission calibration

### Mechanical Engine Modifications

The Vortec 6.0L V8 engine selected provided some unique advantages including:

- Available with desired truck platform
- Alt Fuel Engine option (CNG & Propane) available that provides internal components designed for traditional alternative gaseous fuels that is also beneficial for use with Hydrogen
- High horsepower rating of 300 hp @ 4400 rpm (gasoline fuel)
- High torque rating of 360 lb-ft @ 4000 rpm (gasoline fuel)



Standard Vortec 6000 V8 (Pictured - SS Max Version)



Performance goals were established early on in the development program that focused on a “lean-burn” strategy to achieve very low NOx emissions while trying to maintain acceptable horsepower and torque performance for the Silverado HD1500 truck platform. Integration of a Lysholm supercharger to the intake manifold and large liquid- to-air intercooler provide the added air-boost to meet this requirement. Gaseous fuel injectors designed for use with Hydrogen are installed on the engine using custom fuel rails with fuel temperature and pressure sensors. Additional engine modifications include the integration of an OEM electronic throttle and replacement of the standard spark plugs with custom plugs designed to operate in the Hydrogen fuel environment.



Vortec 6.0L V8 with Supercharger and Intercooler Installed

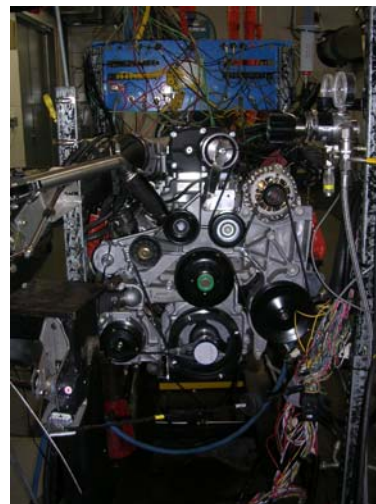
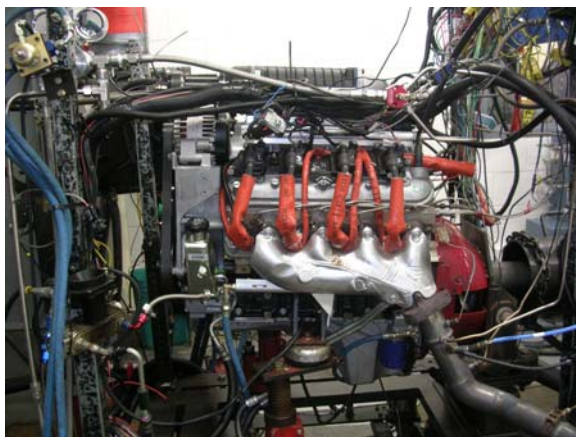
Summarizing the engine modifications:

- ✓ Integration of Lysholm supercharger to intake manifold
- ✓ Integration of large liquid to air intercooler
- ✓ Integration of OEM electronic throttle
- ✓ Integration of fuel-specific fuel injectors, fuel rails and sensors
- ✓ Selection of spark plugs for operation in hydrogen combustion environment



### Engine control hardware and software integration

In order to calibrate the engine and transmission properly, the original Powertrain Control Module had to be replaced with an appropriate aftermarket PCM. The HICE modified engine was then installed on one of Roush's engine dynamometers for proper engine mapping and calibration (shown in the picture below). A significant amount of time and cost in labor hours setting up and operating the engine dyno for the HICE engine and the hydrogen fuel during the testing was expended, but this activity is an absolute requirement to properly map and calibrate the HICE engine. The PCM employed for this conversion allows for sophisticated math modeling of engine processes which result in precise control of air/fuel ratios as well as typical cold-start, engine accessory and transient issues.



HICE Engine on Roush Dynamometer

430 S 2<sup>nd</sup> Avenue Phoenix Arizona 85003

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Summary of engine control hardware and software integration efforts:

- ✓ Complete removal of OEM Powertrain Control Module (PCM)
- ✓ Selection and integration of appropriate aftermarket PCM
- ✓ Development of engine control strategies and math modeling for hydrogen lean-burn operation

### HICE Silverado Fuel System and Engine Integration

The H<sub>2</sub> fuel system design was provided by project partner Powertech Labs and includes the storage tanks, valves, regulators and piping. The storage consists of three 150 liter, Type 3 (aluminum lined, carbon-fiber reinforced), 350 bar (5000 psi) storage pressure tanks. The storage tanks provide 10.5 kg (10.5gge) of usable fuel and together with the installation, meet the latest fuel system standards including NFPA 52, CSA B51 Part 2 and CSA HGV-2 (proposed) standard. The pictures below show the integration steps of the fuel storage system and the HICE engine integration.





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## HICE Silverado Final Engine and Transmission Calibration

In addition to engine control, the OEM PCM also controlled transmission operation and provided vital information for the proper operation of the instrument cluster. Two prototype vehicles were constructed to allow for in-vehicle calibration of the powertrain (engine and transmission) Final engine and transmission calibration was performed in various regions around the country to ensure that the HICE engine performs as it should in various climates and elevations. These regions included Detroit Michigan, Phoenix Arizona and Flagstaff Arizona (higher elevation). A subcontractor was enlisted to reverse-engineer the J1850 messaging for this vehicle. With this information, software was written for the new PCM to allow for proper communication to other vehicle control systems and to ensure proper operation of accessories such as the air conditioning system.

Summary of final engine and transmission calibration efforts:

- ✓ Development of matching transmission control strategies
- ✓ Reverse engineering J1850 message list
- ✓ Creation and implementation of communication software to maintain seamless integration with existing OEM vehicle equipment





## Description & Specifications of the ETEC HICE Silverado 1500HD Truck

The HICE Silverado is an OEM-quality conversion of a Chevrolet Silverado/GMC Sierra 1500HD Pickup Truck modified to operate the GM Vortec 6.0 Liter V8 gasoline engine on 100% hydrogen fuel. The fuel system was designed by Powertech Labs to the latest existing and proposed standards. Engine calibration and vehicle integration services were performed by Roush Industries utilizing their state-of-the-art engine dynamometer facility and experienced engine calibration and vehicle integration professionals.

### Performance Specifications:

Vehicle Range:	237 km (147 miles) City 339 km (210 miles) Highway
Horsepower:	146kW (195 hp)
Torque:	352Nm (260 lbs-ft.)
Top Speed:	161 km/hr (100 m/hr) (Est.)
Fuel Economy:	22.5 km/kg City / 32.3 km/kg Highway (14 mpg City /20 mpg Highway <sup>1</sup> )

### Weight:

Curb Weight:	2864 kg (6300 lbs.)
GVWR:	3909 kg (8600 lbs.)

### Standard Features

6.0 Liter V8  
4-Speed Automatic  
EPA Class: Light duty pickup truck  
Seat Positions: Six  
Power Locks and windows  
Front and Rear Disk Brakes  
Power Steering  
Dual Airbags  
AM/FM Stereo w/ CD Player  
Air Conditioning

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<sup>1</sup> Estimated 9/2006 - Based on test data obtained at Argonne National Laboratory  
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### Vehicle Modifications (Engine and Fuel System)

Supercharged and intercooled  
Electronic throttle  
Powertrain control system custom calibrated for H<sub>2</sub> Fuel  
Compressed Hydrogen with electronic fuel injection  
Three 150 liter tanks, Type 3 (aluminum lined, carbon-fiber reinforced) 350 bar (5000 psi) storage pressure  
10.5kg (10.5 gge) usable fuel  
Meets latest NFPA 52, SA B51 Part 2 and CSA HGV-2 (proposed) standard

### Emissions Testing

In July of 2006, emissions tests were conducted at Argonne National Labs as shown below. These tests were conducted as part of the ETEC/ETA contract with the US Department of Energy (DOE) Advanced Vehicle Testing Activity (AVTA). The truck tested in July was a 2005 Chevrolet Silverado 1500 HD.





For this round of testing, ANL & ETEC conducted a full coastdown test to determine the actual road loads for this vehicle in this configuration. The only coastdown data available from the US Environmental Protection Agency is for a generic Silverado pickup truck equipped with a four-wheel-drive system. We felt that this configuration would lead to additional parasitic losses and, thus, adversely affect the emissions results for the HICE trucks which are rear-drive only. As part of the coastdown test, a more representative test weight was determined following the guidelines of SAE J1263 (resulting in a slightly higher test weight than was used originally by the manufacturer for EPA testing). Additionally, this second emissions test event benefited from additional engine calibration work.

Table 1 presents the results of FTP testing:

Table 1: FTP Emissions Results

Date	THC	NOx	COlow	CO <sub>2</sub>	Fuel Economy (mi/kg) <sup>2</sup>
7/11/2006	0.0000	0.0579	0.0842	0.00	13.89
7/12/2006	0.0009	0.0641	0.0528	0.19	14.03

<sup>2</sup> Fuel economy is calculated using a hydrogen mass flow meter, total miles driven during each of the three phases, and a standard calculation for weighting the results for the three phases



Table 2 presents results for the HWY FET tests.

Table 2: HWY FET Emissions Results

Date	THC	NOx	COlow	CO <sub>2</sub>	Fuel Economy (mi/kg) <sup>1</sup>
7/11/2006	0.0009	NA <sup>3</sup>	0.0297	1.10	21.02
7/12/2006	0.0000	0.0270	0.0478	0.00	20.57

All values are g/mi with the exception of Fuel Economy (mi/kg).

These test results show some amount of CO<sub>2</sub> which is unexpected for hydrogen combustion. Engineers at Argonne National Labs continue to look into this issue. There is a theory that a nearby building that is testing large locomotive engines may be providing a source of intermittent elevated CO<sub>2</sub> levels that are not properly accounted for in regular background level measurements.

In June, 2005, this same truck was tested in its original gasoline configuration after accumulating 7000 miles of typical driving. These tests were conducted at Roush Industries' vehicle emissions facilities using state-of-the-art equipment. As a coastdown test had not been conducted on this vehicle at the time, the coastdown coefficients and test weight used for the dynamometer were selected from the 2005 EPA test results for a Silverado pickup truck. The test weight used was 5250 lb, quite a bit lower than the 6300 lb used for the HICE testing conducted in June, 2006 (see above). As a result, one would expect these values to be optimistic (i.e., lower) for a vehicle with a delivered curb weight near 6000 lb. The results of those tests are presented here for comparison.

Table 3 presents results for the FTP tests.

Table 3: FTP Gasoline Emissions Results

Date	THC	NOx	COlow	CO <sub>2</sub>	Fuel Economy (mi/gal) <sup>1</sup>
06/28/2005	0.130	0.091	1.59	640.9	13.91
06/29/2005	0.122	0.131	1.35	631.1	14.13
06/30/2005	0.127	0.099	1.44	656.2	13.59

<sup>3</sup> NOx values not available due to instrument error



Table 4 presents results for the HWYFET tests.

Table 4: HWYFET Gasoline Emissions Results

Date	THC	NOx	COlow	CO2	Fuel Economy (mi/gal) <sup>1</sup>
06/28/2005	0.00457	0.02106	0.08108	409.52825	21.85
06/29/2005	0.00508	0.02239	0.07279	405.85282	22.05
06/30/2005	0.00494	0.02227	0.08309	408.30910	21.92

All values are g/mi with the exception of Fuel Economy (mi/gal).

It may also be beneficial to compare the most recent HICE emissions numbers to the US EPA certification levels (standards) for model years 2005 and 2006 light duty vehicles. As NOx is the only pollutant of concern with the HICE configuration (given that THC, CO, and CO2 theoretical and measured values are extremely low), only the EPA certification levels for NOx are presented.

US EPA Certification Standards for Light-Duty Gasoline Vehicles (Tier II, Bin 8):

- 2005 & 2006 MY
  - 50k mile NOx level
    - FTP = 0.14 g/mi
    - HWYFET = 0.186 g/mi
  - 100k mile NOx level
    - FTP = 0.20 g/mi
    - HWYFET = 0.266 g/mi

Note that the original gasoline engine as delivered from the manufacturer is rated in the Heavy-Duty category. As such, different, less stringent, emissions standards would have applied to this vehicle. However, it is worth noting that the HICE conversion is capable of meeting (and exceeding) the more stringent standards.

Furthermore, it is worth while to compare the HICE measured emissions values to those specified by Vancouver's AirCare program:

- Driving Mode HC = 1.24 g/km (2.00 g/mi)
- Driving Mode CO = 18.64 g/km (30.00 g/mi)
- Driving Mode NOx = 2.49 g/km (4.01 g/mi)



With these comparison values, it can be seen that the HICE configuration emits less NO<sub>x</sub> on a g/mi basis than the actual measured amounts for the FTP gasoline test as well as the allowable standard amounts for both the US EPA and Vancouver's AirCare program. For the HWYFET test, the results for the HICE configuration is nearly equivalent to the gasoline measured results and is below the values allowed by US EPA and Vancouver's AirCare program.

The US DOE recently awarded ETEC a contract to perform testing and monitoring to determine the durability of HICE systems. Included in this project will be regular emissions test which will shed light on the ability of these vehicles to maintain low NO<sub>x</sub> values as they accumulate mileage.

### **Contact Information:**

Kevin Morrow – ETEC  
602-716-9576 ext.24  
[kmorrow@etecevs.com](mailto:kmorrow@etecevs.com)  
[www.etecevs.com](http://www.etecevs.com)