

DRI investigated practical aspects of hydrogen production, storage and use in transportation applications. As part of the study, DRI collaborated with the Washoe County Regional Transportation Commission (RTC), who is working to convert their bus fleet to utilize hydrogen. With the help of industry partner, Collier Technologies, DRI studied two of RTC's CNG buses, and converted one to use a hydrogen-CNG blend fuel (HCNG). Evaluations of the vehicles' performance and emissions were done before, during and after the conversion through on-road and chassis-dynamometer testing. The results of the testing efforts were used to evaluate the effects of the blend fuel, as well as to update the ADVISOR vehicle modeling software developed by NREL with data for the HCNG blend fuel.

Vehicle Testing Set-Up and Description

Test Vehicle Description

Two 1998 Ford E-350 vehicle using CNG as a fuel were donated to DRI for this study. One vehicle was maintained as a control vehicle and tested as the baseline CNG case. The other vehicle was converted to use an HCNG blend fuel by Collier Technologies.

HCNG Conversion:

The conversion kit used was developed and installed by Collier Technologies. The kit utilizes exhaust gas recirculation (EGR) to take advantage of the charge dilution that the addition of hydrogen allows to reduce the NOx emissions. Cooling of the exhaust gases is achieved by extracting exhaust gas from the lowest temperature exhaust gas source on the vehicle and using the piping that delivers this exhaust gas back to the engine to cool these gases via airflow from vehicle movement. To achieve control over the EGR rate, a separate throttle valve is installed on the EGR line. The throttle valve is connected directly to the air throttle valve of the engine. A supercharger is also included in the conversion kit to offset or reduce the power losses from the less dense H2 blend fuel.



1. 1998 Ford E-350 CNG Test Vehicle



2. Test Vehicle on the Chassis-Dyno

Testing

Testing was completed on:

1. The baseline CNG control bus (some of the tests were done on the conversion CNG bus).
2. The supercharged CNG bus
3. The HCNG converted vehicle with 2 blends of fuel.

Both road and chassis-dynamometer tests included:

- Timed acceleration tests to 55 mph on the road.
- IM240 standard drive cycle tests on the dynamometer.
- Maximum torque and power curve tests on the dynamometer.
- Steady-state power point testing to collect fuel use and emissions data to develop engine maps on the dynamometer.

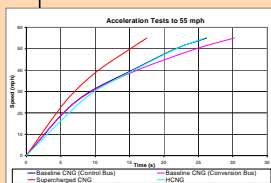
The test equipment used included instruments to measure emissions, fuel use, and vehicle performance. The equipment included:

- Autoenginity OBDII scanner to instantaneously record vehicle speed, engine rpm, throttle position, mass airflow in, and air intake temperature.
- A DJ 5 gas analyzer to instantaneously record CO, CO2, O2, NOx and HC emissions. An ECOM analyzer was used for higher accuracy NOx emissions.
- The dynamometer software was used to measure power, torque, engine speed and vehicle speed measured from the rollers during dyno testing.

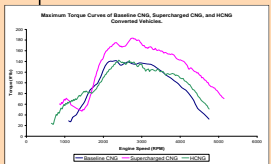
All tests were completed on the baseline CNG control vehicle. Some preliminary tests were completed on the conversion vehicle as a CNG bus that showed the lower performance and higher NOx emissions. The conversion vehicle was selected as a result of these results so that any reduction in NOx emission or changes in performance would not be overestimated.

Testing Results

The two CNG vehicles exhibited slight differences in performance: the conversion vehicle exhibited slightly lower performance and higher NOx emissions than the control vehicle. It was selected for conversion because of this so as not to positively skew the final results.



3. Road acceleration test results of all vehicle platforms



4. Max torque curves for the control CNG, supercharged CNG and HCNG buses.

Acceleration Tests

The acceleration tests were performed on both baseline CNG vehicles, the supercharged CNG vehicle and the HCNG converted vehicle. The supercharged CNG vehicle exhibited the best acceleration performance, and reached 55 mph in 42% less time than it did prior to conversion. Fueling the converted vehicle with HCNG results in a loss of power, however, the acceleration time to 55 mph still decreases by 15% compared to its original case.

Maximum Torque Curve Testing

Maximum torque curve tests were completed on the CNG control bus, the super-charged CNG bus, and the HCNG bus. Max torque tests were not completed on the conversion CNG bus. The HCNG conversion results in a similarly shaped maximum torque curve as the baseline CNG vehicle, with 141 ft*lb of torque at about 2400 rpm. However, the max torque is reduced by 23% from 183 ft*lb produced by the supercharged CNG bus.

IM240 Drive Cycle Tests

The instantaneous fuel use and emissions were recorded during the IM240 drive cycle test on the dynamometer and used to estimate the total fuel use and emissions produced during the cycle. The conversion vehicle exhibits better fuel use and emissions than the control vehicle as a CNG bus. However, comparisons are made between the conversion and the control vehicle, so changes may be underestimated. The conversion to HCNG resulted in similar fuel economy as the baseline control vehicle on a gallon gasoline equivalent basis, however, the range is reduced slightly. The conversion to HCNG compared to the control bus results in:

- ~90% reduction in NOx emissions
- ~80% reduction in CO emissions
- ~15% decrease in CO2 emissions
- ~15% increase in HC emissions.

The steady state point tests were used to develop the engine maps for ADVISOR.

Table 1: Results from all vehicle tests on IM240 cycle. Average of all cycles measured.

	Baseline CNG				Supercharged CNG				85% HCNG				80% HCNG																				
	Test	Sim	Sim	RTC	Test	Sim	Sim	RTC	Test	Sim	Sim	RTC	Test	Sim	Sim	RTC																	
Distance (mi)	1.94	240.1	69.8	47	588	7.58	0.14	3.4	3.4	10.0	1.94	240.1	69.8	47	588	7.58	0.14	3.4	3.4	10.0													
Fuel Use (gpm)	1.93	197.9	30.4	37.6	480	7.73	0.11	4.2	12.3	1.94	219	50.1	42.3	534	7.65	0.13	3.3	9.7	1.94	219	50.1	42.3	534	7.65	0.13	3.3	9.7						
CO (gpm)	1.94	219	50.1	42.3	534	7.65	0.13	3.3	9.7	1.93	220.3	22.1	8.9	504	0.65	0.16	2.7	10.0	1.93	220.3	22.1	8.9	504	0.65	0.16	2.7	10.0						
CO2 (gpm)	1.93	197.9	30.4	37.6	480	7.73	0.11	4.2	12.3	1.94	219	50.1	42.3	534	7.65	0.13	3.3	9.7	1.93	197.9	30.4	37.6	480	7.73	0.11	4.2	12.3						
NOx (gpm)	1.94	219	50.1	42.3	534	7.65	0.13	3.3	9.7	1.93	220.3	22.1	8.9	504	0.65	0.16	2.7	10.0	1.94	219	50.1	42.3	534	7.65	0.13	3.3	9.7						
HC (gpm)	1.94	219	50.1	42.3	534	7.65	0.13	3.3	9.7	1.93	220.3	22.1	8.9	504	0.65	0.16	2.7	10.0	1.94	219	50.1	42.3	534	7.65	0.13	3.3	9.7						
MPG	3.4	3.4	19.3	31	3.3	3.4	1.7	2.3	2.7	10.0	3.4	19.3	31	3.3	3.4	1.7	2.3	2.7	10.0	3.4	19.3	31	3.3	3.4	1.7	2.3	2.7	10.0					
MPGGE	10.0	10.0	5.7	9.3	9.7	10.0	5.1	8.3	10.0	10.0	10.2	4.9	7.0	10.7	5.8	8.4	10.0	10.0	10.0	10.2	4.9	7.0	10.7	5.8	8.4	10.0	10.0	10.2	4.9	7.0	10.7	5.8	8.4

ADVISOR Modeling and Results

Model Description and Set-Up

ADVISOR, which stands for Advanced Vehicle Simulator, calculates the performance and emissions of a vehicle on a specific drive-cycle. The steady-state test data collected was used to develop engine maps in ADVISOR that could be used to model the vehicles' performances. The models were developed using the geometry and parameters specific to the test vehicle. Engine maps were developed for:

- the baseline CNG control vehicle
- the supercharged CNG vehicle
- and HCNG vehicle using a 30% by volume hydrogen blend
- and an HCNG vehicle using a 20% hydrogen blend.

Models of each vehicle were simulated on the following drive-cycles in an effort to verify the results:

- IM240 drive cycle
- Acceleration test

Additional simulations were performed on a cycle developed from data collected from an RTC para-transit bus during its regular operation.

Modeling Results

The performance of the vehicles were underestimated by the model: the maximum torque curves measured on the dynamometer were reduced from losses in the drive-train. Therefore, the engine files developed can only be used for specific vehicles tested. However, the emissions and fuel use estimates of the simulations were quite comparable to those measured on the dynamometer, as shown in Table 2. The baseline CNG model produced the most comparable results to the test data, within 8% of the fuel use and emissions measured. Fuel use estimated for all vehicle simulations was very comparable to the test results. The changes in emissions were comparable to test results for NOx and CO, and the conversion to the 20% HCNG blend modeled on the IM240 cycle results in:

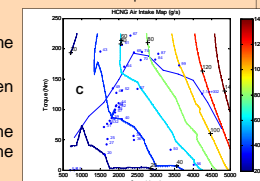
- 85% reduction in NOx emissions
- 75% reduction in CO emissions
- 1% reduction in CO2
- 200% increase in HC emissions

Table 2: ADVISOR Simulation results the IM240 and RTC drive cycles. Test and hybrid results are included.

	Baseline CNG				Supercharged CNG				85% HCNG				80% HCNG			
	Test	Sim	Sim	RTC	Test	Sim	Sim	RTC	Test	Sim	Sim	RTC	Test	Sim	Sim	RTC
Distance	1.94	1.94	19.98	20.52	1.92	1.94	19.93	20.52	1.93	1.94	19.99	20.52	1.94	20.05	20.52	20.52
Fuel Use (gpm)	240	242	426	262	246	243	479	294	220	228	482	306	211	389	270	270
CO2 (gpm)	528	552	1059	624	650	646	1287	798	503	585	1229	757	533	967	685	685
CO (gpm)	47	44	65	44	16	13	22	13	9	11	22	10	10	18	14	14
NOx (gpm)	7.6	7.2	12.8	7.0	9.1	12.6	22.5	12.4	0.7	1.1	1.9	1.0	1.4	2.6	1.3	1.3
HC (gpm)	0.145	0.150	0.262	0.154	0.157	0.180	0.367	0.201	0.165	0.209	0.360	0.300	0.154	0.328	0.231	0.231
MPG	3.4	3.4	19.3	31	3.3	3.4	1.7	2.3	2.7	2.7	1.3	2.0	2.6	1.4	2.0	2.0
MPGGE	10.0	10.0	5.7	9.3	9.7	10.0	5.1	8.3	10.0	10.2	4.9	7.0	10.7	5.8	8.4	8.4



5. ADVISOR input GUI.



6. Fuel use engine map for HCNG bus with 30% hydrogen.

Introduction
 •NREL funded project through the Nevada Southwest Energy Partnership (NSWEP)
 •Focus on development and deployment on hydrogen in transportation applications
 •The performance and emissions effects of converting a vehicle from compressed natural gas (CNG) to hydrogen-compressed natural gas (HCNG) were studied via chassis-dynamometer and road testing.
 •Two Ford 1999 E-350 vehicle fueled by CNG were evaluated for a baseline performance.
 •One vehicle was converted to HCNG using a conversion kit developed by Collier Technologies.
 •The converted vehicle was evaluated both as a supercharged CNG vehicle and an HCNG vehicle.
 •The data from the testing was also used to develop software for ADVISOR model.

