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# Controlled Hydrogen Fleet and Infrastructure Demonstration and Validation Project: Data Analysis Overview

## Preprint

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# CONTROLLED HYDROGEN FLEET AND INFRASTRUCTURE DEMONSTRATION AND VALIDATION PROJECT: DATA ANALYSIS OVERVIEW

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## Abstract

Early in 2003, the U.S. Department of Energy (DOE) initiated a solicitation titled the "Controlled Hydrogen Fleet and Infrastructure Demonstration and Validation Project." The purpose of this project is to conduct an integrated field validation that simultaneously examines the performance of fuel cell vehicles and the requisite hydrogen infrastructure. The integrated nature of the project enables demonstration and validation of complete system solutions for hydrogen-powered transportation. Insights from the vehicles and infrastructure will be fed back into DOE's research and development program to guide program structure and to refocus future research, making this project a "learning demonstration."

Five teams were selected and four cooperative agreements between DOE and industry partners were awarded in fiscal year 2004. These four cooperative agreements support more than 120 fuel cell vehicles, which will be validated on road, as well as about 28 hydrogen refueling stations. Many fuel cell vehicles have already entered into service with real customers, and new hydrogen refueling stations have opened, with more vehicles and stations planned. Estimated government investment in this project will be about $190 million; with cost share from industry, total projected expenditures are about $400 million.

This DOE/industry collaborative project will continue for 5 years, during which multiple generations of technology will be tested. Technical performance of vehicles and infrastructure will be compared against DOE targets at intermediate stages and at project completion. Examples of 2009 DOE targets include a 250-mile vehicle range, 2,000-hour durability of vehicle fuel cell stacks, and a hydrogen production cost of $3/gge untaxed, when produced in quantity.

This paper provides an overview of key objectives and targets of the demonstration and validation project. The partners involved are discussed, and a summary of the data collected and the data collection and analysis process is provided. Finally, examples of specific analyses to be performed during the project are shown.

**Key words:** demonstration, fuel cell, hydrogen, infrastructure, vehicle.

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# 1. Introduction

Hydrogen fuel cell vehicles are being developed and tested for their potential as commercially viable and highly efficient zero-tailpipe-emission vehicles. Using hydrogen fuel and high-efficiency fuel cell vehicles provides environmental and fuel feedstock diversity benefits to the United States. Hydrogen could be derived from a mixture of renewable sources, natural gas, biomass, coal, and nuclear energy, enabling the United States to reduce emissions and decrease its dependence on foreign oil. Numerous technical barriers remain before hydrogen fuel cell vehicles are commercially viable. Significant resources from private industry and government are being devoted to overcome these barriers.

The U.S. Department of Energy (DOE) is working with industry to facilitate commercialization of these technologies through its Hydrogen, Fuel Cells & Infrastructure Technologies (HFCIT) Program. This multi-faceted program simultaneously addresses hydrogen production, storage, delivery, conversion (fuel cells), technology validation, deployment (education), safety, and codes and standards. Many key technical barriers, such as hydrogen storage and fuel cell durability, have been identified and are being addressed. Additional challenges may become apparent through integrated, real-world application of these technologies. To date, the number of fuel cell vehicles in service has been small, and vehicle operation has been focused primarily in California, limiting the quantity and geographic diversity of data collected. To address vehicle and refueling infrastructure issues simultaneously, DOE is conducting a large-scale "learning demonstration" involving automotive manufacturers and fuel providers. This learning demonstration, titled the "Controlled Hydrogen Fleet and Infrastructure Demonstration and Validation Project," is the second phase of the HFCIT Program's Technology Validation effort (see Figure 1).

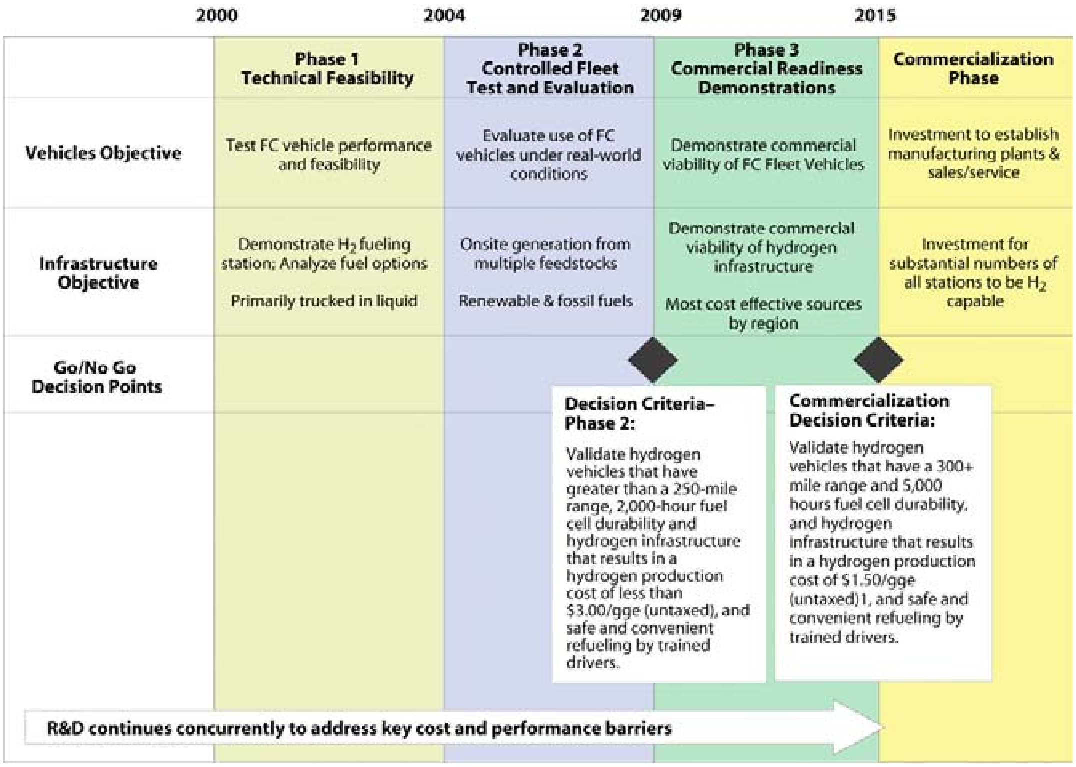



Figure 1: Transportation and Infrastructure Timeline

In April 2003, DOE initiated a competitive solicitation for proposals for this project. Five teams were selected and four cooperative agreements between DOE and industry partners were awarded in fiscal year 2004. These four agreements support more than 120 fuel cell vehicles, which will be validated on road, as well as about 28 hydrogen refueling stations. Many fuel cell vehicles have already entered into service with real customers, and new hydrogen refueling stations have opened, with more vehicles and stations planned. Estimated government investment in this project will be about $190 million; with cost share from industry, total projected expenditures are about $400 million

## 2. Project Objectives and Targets

One of the HFCIT Program's key objectives is to conduct parallel learning demonstrations of hydrogen infrastructure and fuel cell vehicles to facilitate an industry commercialization decision by 2015. By doing so, the project will demonstrate and validate complete system solutions. The quantity and breadth of data collected and analyzed will enable evaluation of technology status versus DOE program targets as well as refocusing of DOE-funded research and development. The ability to refocus research and development is part of what makes this project unique.

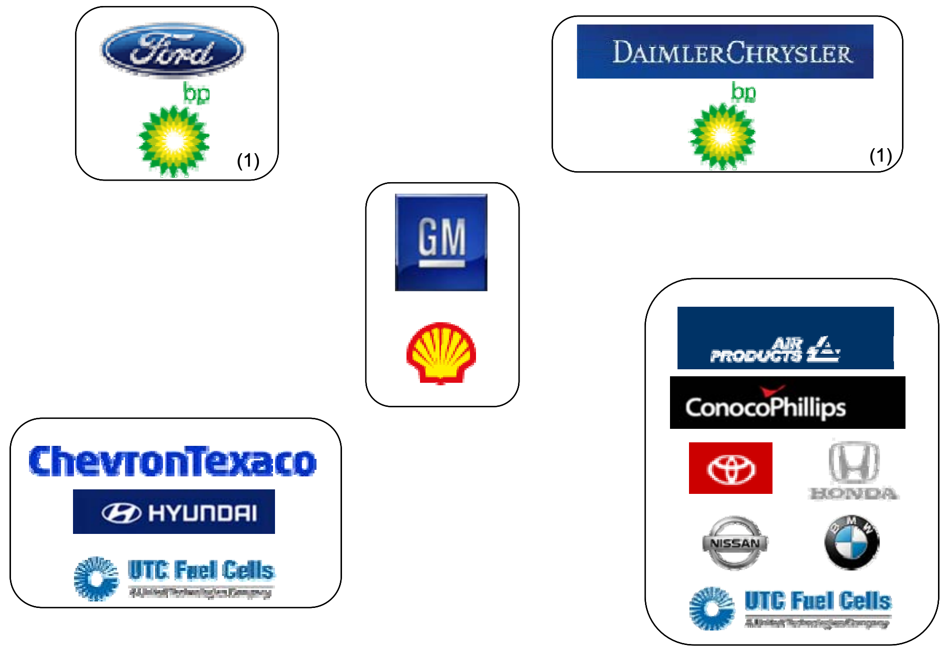
This project has specific performance targets for 2009, which will be used to evaluate progress toward the 2015 targets. The targets listed in Table 1 address key barriers to successful market entry. Fuel cell stack durability is critical to customer acceptance of fuel cell vehicles. Although 2,000-hour durability in 2009 is considered acceptable to demonstrate progress, a 5,000-hour lifetime (equivalent to approximately 100,000 miles) is estimated as a requirement for commercialization. Vehicle range is also an important consumer expectation. Although many factors contributed to the failure of all-electric vehicles to gain market acceptance despite California government mandates, limited vehicle range is widely accepted as being a significant contributor. Finally, hydrogen production cost is a key metric because consumers are much less likely to purchase an alternative fuel vehicle if the fuel is significantly more expensive than gasoline.

| **Key Targets** | | |
|---|---|---|
| **Performance Measure** | **2009*** | **2015**** |
| Fuel Cell Stack Durability | 2000 hours | 5000 hours |
| Vehicle Range | 250+ miles | 300+ miles |
| Hydrogen Cost at Station(untaxed) | $3.00/gge | $1.50/gge |
| * To verify progress toward 2015<br>** Subsequent projects to validate 2015 target | | |

Table 1: Project Performance Targets

## 3. Cooperative Agreements

DOE selected five teams and awarded cooperative agreements to four of those teams in fiscal year 2004. This section illustrates the five teams selected and describes in more detail the four teams that have been awarded cooperative agreements to date. The DOE solicitation required each team to include an automotive original equipment manufacturer (OEM) and an energy provider and that the OEM or energy provider be the team leader. An automotive OEM is the leader of three of the teams, and an energy provider is the leader of one. Figure 2 shows the five teams selected by DOE. Figure 3 shows examples of fuel cell vehicles developed by the teams awarded cooperative agreements, which will be validated during this project.




(1) Fuel cells supplied by Ballard

Figure 2: Five Teams Selected by DOE

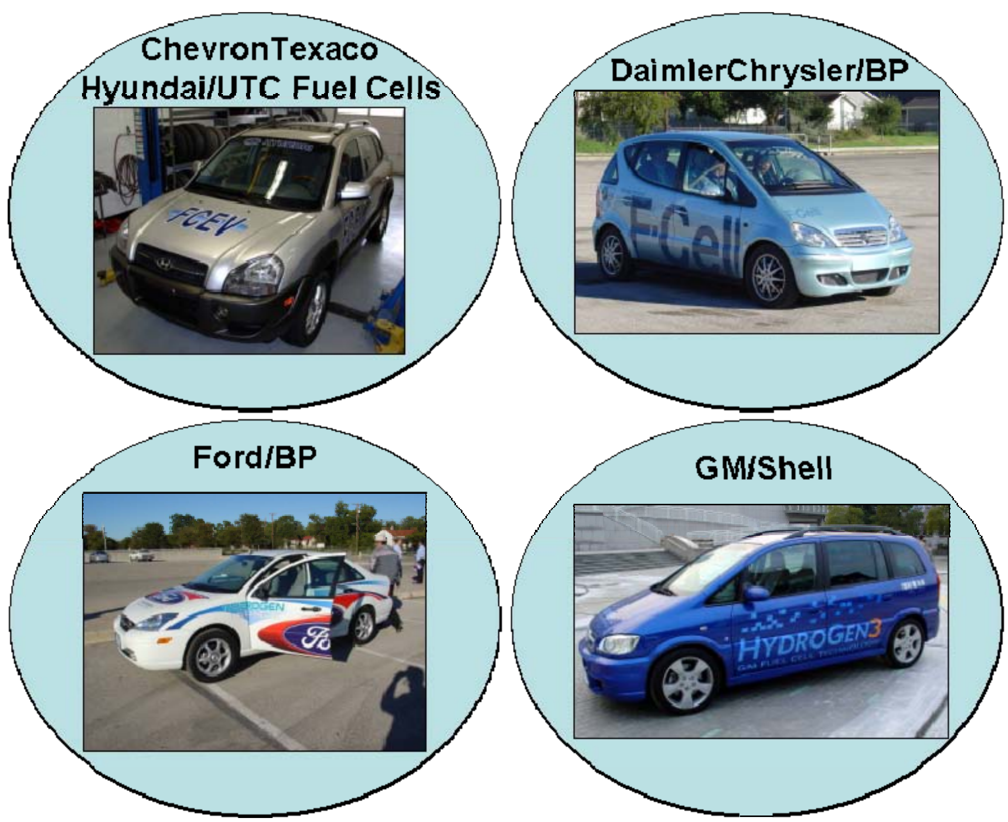



Figure 3: Fuel Cell Vehicle Examples

### 3.1. ChevronTexaco, Hyundai Motor Company, and UTC Fuel Cells

ChevronTexaco is teaming with Hyundai Motor Company and UTC Fuel Cells for this project. The team's fleet will include approximately 32 Hyundai Tucson sport utility vehicles. During the 5-year project, two different generations of fuel cell systems from UTC Fuel Cells will be tested. Approximately six refueling stations in northern and southern California will service the fleet.

### 3.2. DaimlerChrysler and BP

DaimlerChrysler is teaming with BP for this project, with Ballard supplying the fuel cells. The team's fleet will include approximately 36 fuel cell vehicles, most of which are Mercedes-Benz F-Cell vehicles. Some Dodge Sprinter vans also will be tested. One goal is to introduce more than one generation of fuel cells into service during the project so that improvements from ongoing research can be validated. Approximately eight refueling stations in northern California, southern California, and the Detroit, Michigan area will service the fleet.

### 3.3. Ford Motor Company and BP

Ford Motor Company is teaming with BP for this project, with Ballard supplying the fuel cells. The team's fleet will include approximately 26 Ford Focus fuel cell vehicles, which will be serviced by approximately seven refueling stations in northern California, the Detroit, Michigan area, and central Florida. Two generations of fuel cells will be demonstrated during this project.

### 3.4. General Motors and Shell

General Motors is teaming with Shell for this project and will be providing its own fuel cell stacks to power its vehicles. The team's fleet will include approximately 40 fuel cell vehicles (primarily Opel Zafira minivans), which will be serviced by approximately seven refueling stations in northern and southern California, the Detroit, Michigan area, and the northeastern United States. Two generations of fuel cells will be demonstrated during this project.

## 4. Data Collection and Analysis Process

To enable DOE to identify technology status and refocus DOE-funded research and development, a large amount of data will be collected and analyzed during the learning demonstration. Table 2 shows a high-level summary of the data to be collected.

| Key Vehicle Data | Key Infrastructure Data |
|---|---|
| Stack Durability | Conversion Method |
| Fuel Economy (Dyno & On-Road) and Vehicle Range | Production Emissions |
| Fuel Cell System Efficiency | Maintenance, Safety Events |
| Maintenance, Safety Events | Hydrogen Purity/Impurities |
| Top Speed, Accel., Grade | Refueling Events, Rates |
| Max Pwr & Time at 40C | $H_2$ Production Cost |
| Freeze Start Ability (Time, Energy) | Conversion, Compression, Storage and Dispensing Efficiency |
| Continuous Voltage and Current (or Power) from Fuel Cell Stack, Motor/Generator, Battery & Key Auxiliaries: (Dyno & On-Road) | |

Table 2: Key Vehicle and Infrastructure Data

Vehicle and infrastructure validation will take place in five different geographic regions (Figure 4). Table 3 summarizes the different climates in these regions. Operating vehicles in a variety of climates is important because each climate presents a different technical challenge. Cold climates permit evaluation of a fuel cell vehicle's ability to start and operate in sub-zero temperatures, a key threshold for a fuel cell system that requires humidification and produces water during operation. Hot environments permit evaluation of the system's ability to reject heat while keeping the fuel cell stack membranes adequately humidified. Fuel cell systems operate at lower temperatures than internal combustion engines (ICEs), making heat rejection more challenging and typically requiring a larger radiator. All the regions include moderate conditions during the year, which should permit comparing performance of a large number of vehicles under similar environmental conditions.

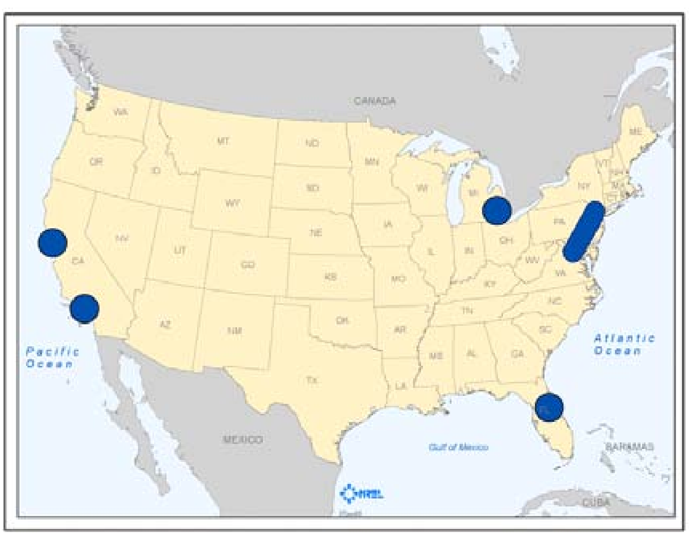



Figure 4. Hydrogen Fueling Station Locations

| Station/Vehicle Location | Climate | | | |
|---|---|---|---|---|
| | **Cold** | **Moderate** | **Hot, Humid** | **Hot, Arid** |
| Northern California | | X | | X |
| Southern California | | X | | X |
| Detroit, Michigan | X | X | | |
| Washington, D.C./NYC | X | X | X | |
| Orlando, Florida | | X | X | |

Table 3: Climates Represented by Learning Demonstration Locations

Because most of the data to be collected are highly confidential and represent the result of several hundred million dollars of development effort, considerable attention is being given to data security. Figure 5 provides an overview of the data collection and analysis process for this project.

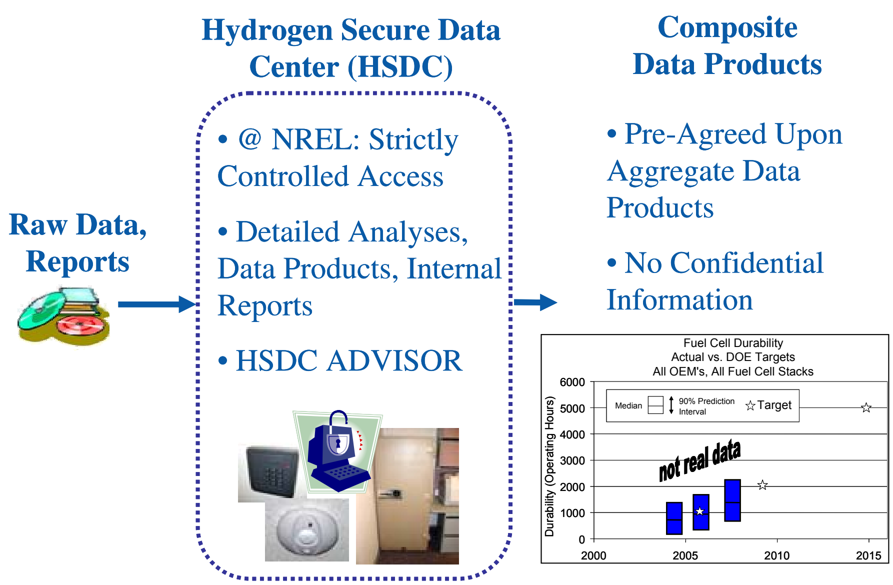



Figure 5: Data Collection and Analysis Process Overview

Raw data and reports from partner companies will be delivered to the Hydrogen Secure Data Center (HSDC), located at the National Renewable Energy Laboratory (NREL) in Golden, Colorado. Access to the HSDC is strictly controlled and limited to a few individuals within NREL and DOE. Detailed analyses and reports will be generated within the HSDC, the results of which will be available only to the limited number of individuals authorized to enter the HSDC. Included in the HSDC analysis will be a version of ADVISOR™ (Advanced Vehicle Simulator), termed the "HSDC ADVISOR" model. HSDC ADVISOR will contain models of fuel cell vehicles developed and validated using data provided by partners. However, HSDC ADVISOR will not be made public and is only accessible to HSDC-authorized individuals. The only data products permitted to leave the HSDC are termed "Composite Data Products" and are agreed upon in advance with each partner company. These data products will contain no confidential information and will display only aggregate data from the partners. For instance, the composite data products will contain ranges of performance values, and the performance of individual companies will not be distinguishable. Table 4 shows the 25 composite data products developed and agreed upon among DOE and all industry partners.

| **Critical Program Metrics** |
|---|
| 1. Fuel Cell Durability, Actual vs. DOE Targets, All OEMs |
| 2. Vehicle Ranges, Actual vs. DOE Targets, All OEMs |
| 3. Hydrogen Production Cost, Actuals/Projections vs. DOE Targets |
| **Composite Performance Tracking** |
| ***Vehicles*** |
| 4. Reliability (Fuel Cell System & Powertrain, MTBF) |
| 5. Start Times vs. DOE Target |
| 6. Fuel Economy: Dynamometer, On-Road |
| 7. Normalized Vehicle Fuel Economy |
| 8. Fuel Cell System Efficiency |
| 9. Safety Incidents - Vehicle Operation |
| 10. Weight % Hydrogen Stored |
| 11. Energy Density of Hydrogen Storage |
| 12. Vehicle Hydrogen Tank Cycle Life |
| ***Hydrogen Infrastructure*** |
| 13. Hydrogen Production Efficiency vs. Process |
| 14. Combined Heat and Power (CHP) Efficiencies |
| 15. Hydrogen Production Cost vs. Process |
| 16. Hydrogen Purity vs. Production Process |
| 17. Hydrogen Impurities - Range for Production Process "A" |
| 18. Histogram: Refueling Rate |
| 19. Average Maintenance Hours - Scheduled and Unscheduled |
| **High-Level Program Progress** |
| ***Vehicles*** |
| 20. Range of Actual Ambient Temperatures During Vehicle Operation - All Vehicle Teams |
| 21. Histogram: # Vehicles vs. Operating Hours to Date |
| 22. Histogram: # Vehicles vs. Miles Traveled to Date |
| 23. Cumulative Vehicle Miles Traveled - All Teams |
| 24. Progression of Low- to High-Pressure On-board Hydrogen Storage |
| ***Hydrogen Infrastructure*** |
| 25. Cumulative Hydrogen Production - All Teams |

Table 4: Composite Data Products

These composite data products permit the government to report progress toward targets and publish mid-course program changes without compromising any company's data or competitive advantage. The data are also used to identify trends and significant technology issues that current research may not adequately address. Figure 6 and Figure 7 show two examples of composite data products that will be published as the information becomes available. As sufficient data do not yet exist to report actual values for these data products, fictitious data (with the exception of targets, which are real) have been inserted in these figures for illustration only.

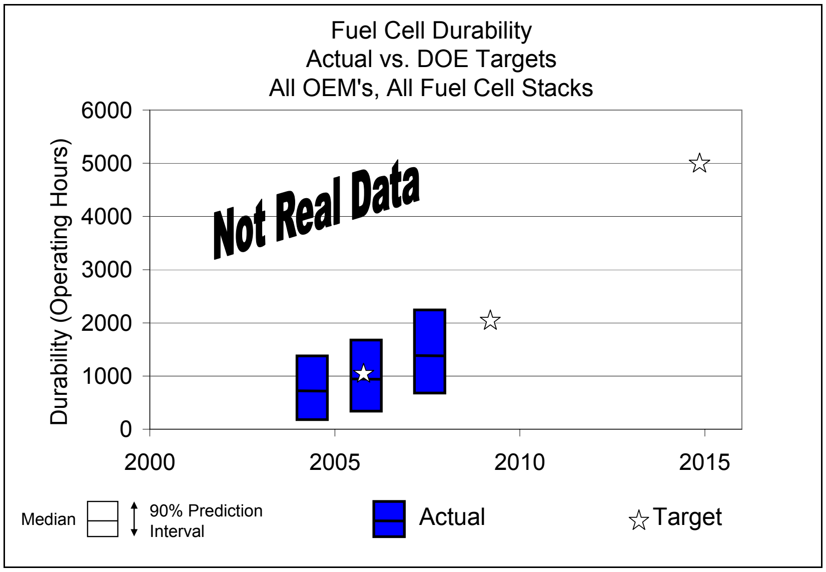



Figure 6: Example Composite Data Product: Fuel Cell Durability

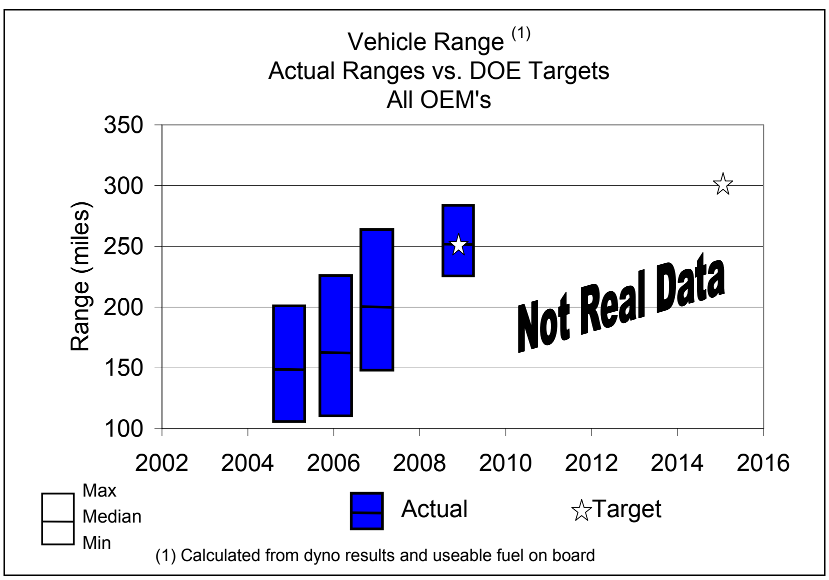
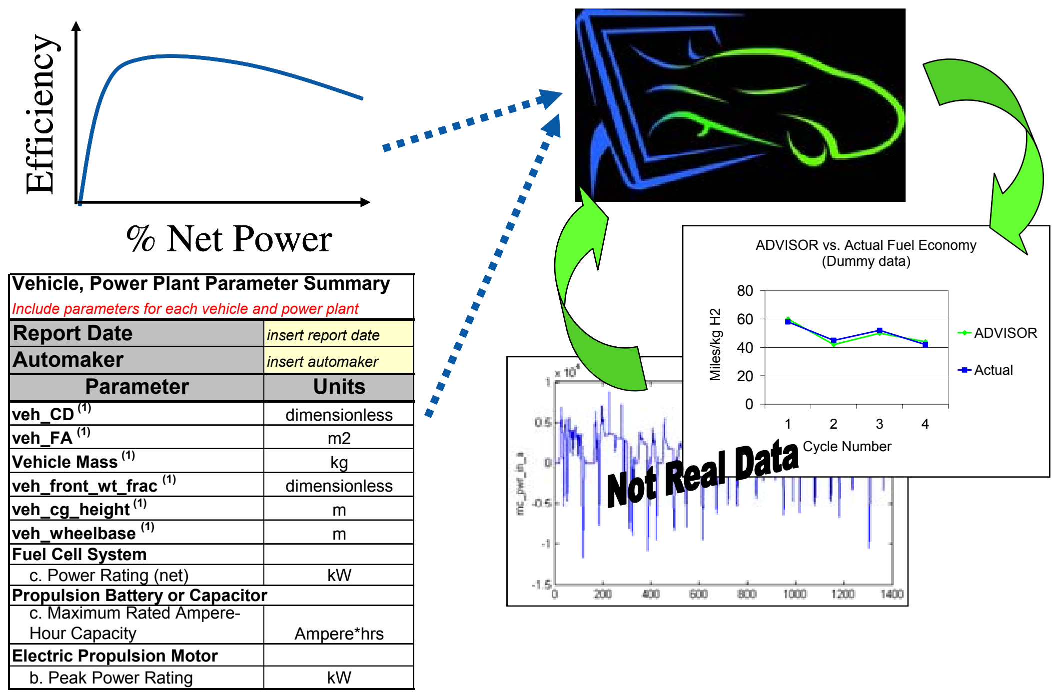



Figure 7: Example Composite Data Product: Vehicle Range

## 5. Data Analysis Examples

### 5.1. HSDC ADVISOR

Starting with the latest version of ADVISOR, NREL plans to create vehicle models for each OEM fuel cell vehicle. Model structure and parameters will be modified as required to ensure good agreement between model performance and actual vehicle performance. This version of ADVISOR is referred to as HSDC ADVISOR because model structure and parameter changes will remain within the HSDC. A combination of data from vehicle OEMs—such as power plant and vehicle parameters, fuel cell system efficiency curves, and second-by-second data collected during dynamometer tests and on-road operation—will be used to validate the HSDC ADVISOR models. Figure 8 shows this iterative process.




| Vehicle, Power Plant Parameter Summary | |
|---|---|
| *Include parameters for each vehicle and power plant* | |
| **Report Date** | *insert report date* |
| **Automaker** | *insert automaker* |
| **Parameter** | **Units** |
| **veh_CD** (1) | dimensionless |
| **veh_FA** (1) | m2 |
| **Vehicle Mass** (1) | kg |
| **veh_front_wt_frac** (1) | dimensionless |
| **veh_cg_height** (1) | m |
| **veh_wheelbase** (1) | m |
| **Fuel Cell System** | |
| c. Power Rating (net) | kW |
| **Propulsion Battery or Capacitor** | |
| c. Maximum Rated Ampere-Hour Capacity | Ampere*hrs |
| **Electric Propulsion Motor** | |
| b. Peak Power Rating | kW |

Figure 8: HSDC ADVISOR Model Validation Process

Once NREL has confidence that the HSDC ADVISOR models correspond well with actual vehicle performance, a number of analyses may be performed to inform DOE of the technology status and the effect of changes in component performance targets. This type of analysis can help DOE determine whether future research and development funding is needed in a particular area. Validated models also will permit normalized comparisons to be made of fuel cell vehicles from different OEMs. For instance, a common vehicle platform (e.g., mass, coefficient of drag, frontal area) may be chosen for fuel economy modeling, with the only major difference in the models being the fuel cell system. Without such models to facilitate normalization, the confounding effects of vehicle type and system performance would not permit such comparisons to be made.

## 5.2. Fuel Cell Stack Degradation Analysis

NREL will conduct detailed statistical analyses of the fuel cell stack voltage and current to gain insight into stack degradation. Because essentially continuous voltage and current data will be obtained from several, or in many cases all, vehicles in each fleet, a robust statistical basis for this analysis should be possible.

A scatter plot of fuel cell stack voltage versus current for a given period of stack operation will reveal the shape of the fuel cell stack polarization curve. Figure 9 shows an example fuel cell stack polarization curve, illustrating the various losses that exist in a fuel cell stack.

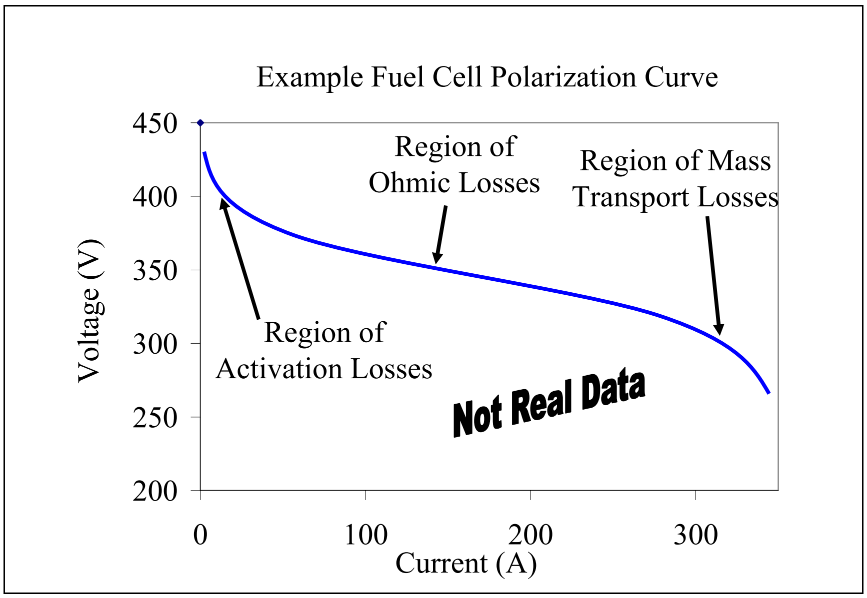



Figure 9: Example Fuel Polarization Curve

Using any of several curve-fitting programs, non-linear least squares regression can be used to fit the scattered voltage and current data to the following equation:

$$V = \underbrace{a}_{\text{Ideal Voltage}} - \underbrace{b * \log(current)}_{\text{Activation Losses}} - \underbrace{c * (current)}_{\text{Ohmic Losses}} - \underbrace{d * \exp(e * (current))}_{\text{Mass Transport Losses}}$$

Equation 1: Polarization Curve Fit Equation

However, the design point for operating the stack in a vehicle is typically such that stack current will be less than would be required to observe the effects of mass transport losses. Therefore, when fitting a curve to scattered voltage and current data for a stack operating in a vehicle, parameters "d" and "e" in Equation

1 usually will not be statistically significant. In many cases, curve-fitting algorithms will not yield a solution when the last term of Equation 1 is included in the curve-fit model. To avoid this situation, the last term of Equation 1 typically can be omitted from the curve-fit process without losing the ability to obtain a reasonable fit of the data. Equation 2 shows the resulting model used for fitting the fuel cell polarization curve.

$$V = a - b * \log(current) - c * (current)$$

Equation 2: Polarization Curve Fit Equation - No Mass Transport

Because voltage and current data are provided by the partners throughout the life of the vehicle, it should be possible to evaluate changes in the predicted stack voltage as a function of stack current by looking at the change in the curve-fit of the scattered data versus time. Figure 10 shows the results of an analysis conducted using simulated voltage and current data. NREL generated the example data in Figure 10 using ADVISOR for a fictitious vehicle system combined with post-processing MATLAB scripts to give the data realistic noise and degradation trends. The upper graph of Figure 10 shows the scattered voltage and current data at one point in time (t = 344 hours), the curve-fit of the scattered data, and the confidence intervals for the predicted voltage. In this example, a new curve-fit was calculated for approximately every 12 hours of simulated stack data. The lower graph of Figure 10 illustrates how the predicted voltage changes as a function of vehicle operating hours and stack operating current.

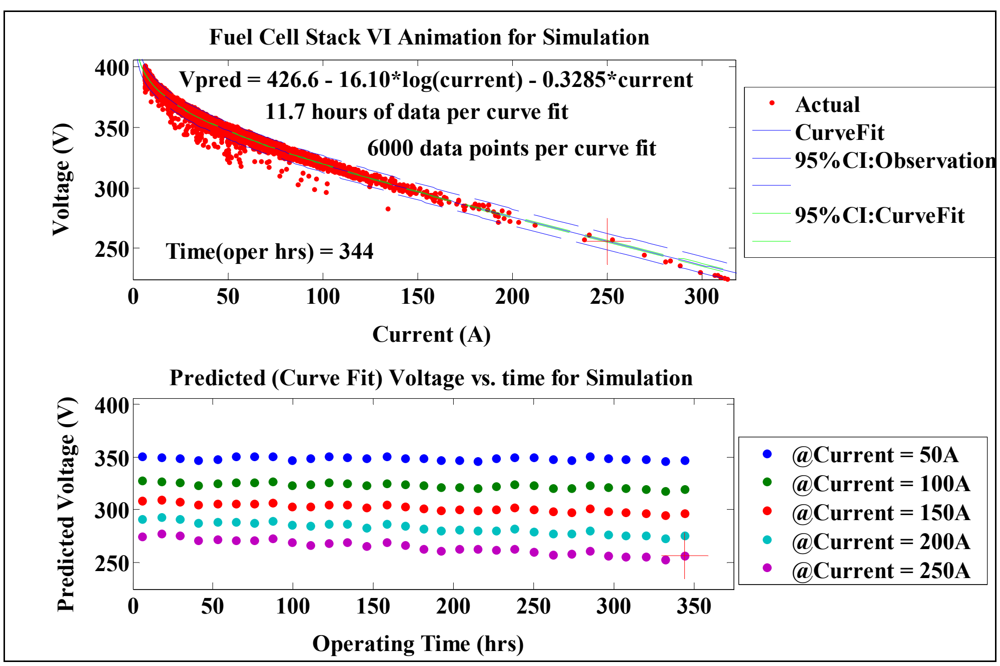



Figure 10: Polarization Curve Fitting

To evaluate the voltage degradation, further analysis of the change in the predicted voltage is required. In this example, linear regression of the predicted voltage as a function of operating hours was performed (Figure 11). If the real data do not fit a linear regression, non-linear curves may be used.

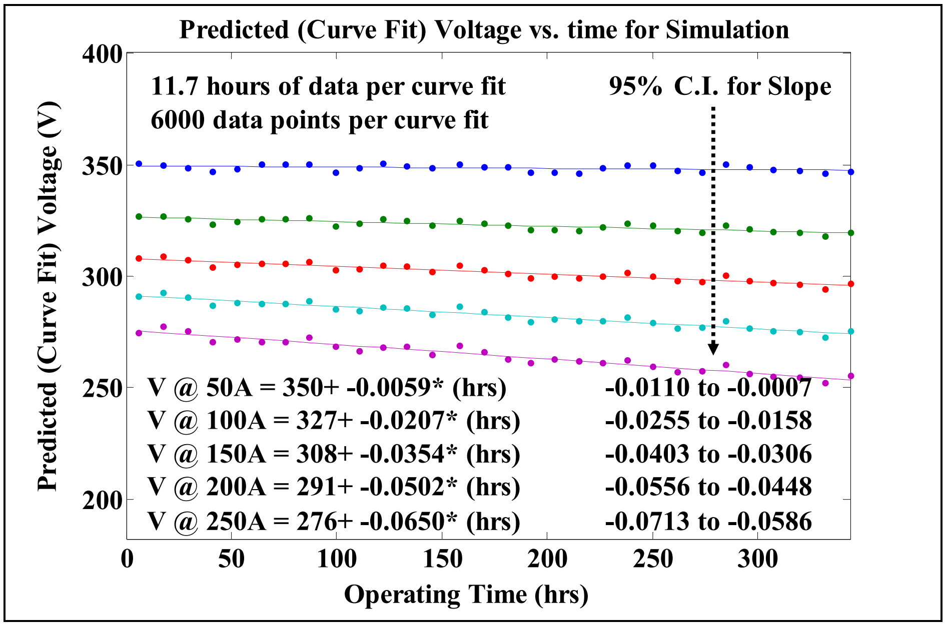



Figure 11: Linear Regression of Predicted Voltage vs. Time

As seen in Figure 11, the confidence intervals of the slopes of each linear regression also were calculated to provide an understanding of the statistical significance of the predicted rate of voltage loss. Regression can be performed for the predicted voltage loss at any current; five current values were chosen for the above example.

Although several curve-fitting software tools can be used to conduct this type of analysis, the above curve-fits were calculated using MATLAB. The advantage of MATLAB over other statistical programs is that it permits user-friendly and automated analysis, plotting, animation, and storage of results. NREL wrote several scripts to generate the above graphs, curve-fits, and confidence intervals. As a result, this analysis can be performed with a single command line execution in MATLAB for any vehicle. Other statistical packages are not as conducive to such automated analyses and reporting, which will be necessary because of the large volume of data expected over the course of this project.

In addition to providing insight regarding the rate of stack degradation, this type of analysis also may shed light on dominant decay mechanisms. Examining how the shape of the polarization curve-fit changes with time may show whether voltage losses are due to increases in the activation losses (e.g., by observing an overall drop in the curve), increases in the ohmic losses (e.g., by observing a slope change), or appearance of the mass transport region of the polarization curve. Figure 12 shows examples of various changes in the shape of the polarization curve.

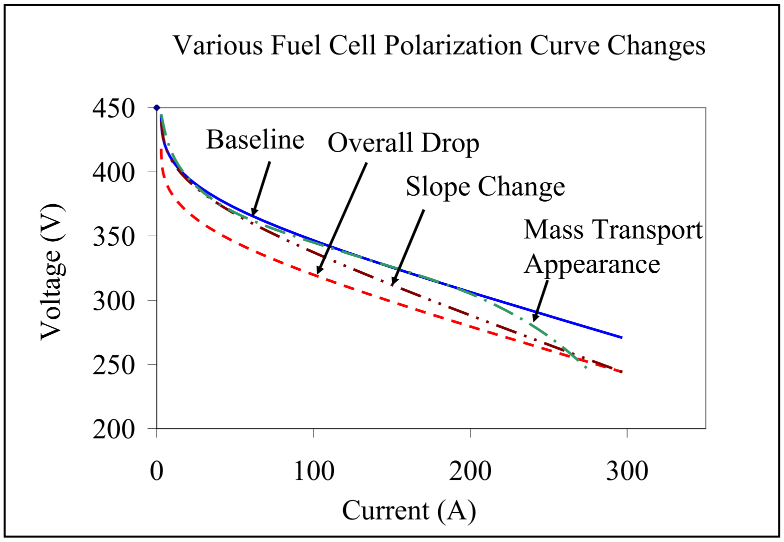



Figure 12: Various Polarization Curve Changes

Although each type of shape change could have several different root causes, understanding the shape change could help researchers focus their resources. Significant additional fuel cell stack data analysis would be required before general statements could be made about the utility of such an approach, but it appears promising. Once sufficient data are available, NREL will begin sharing the results of its analysis with the individual partner involved. This analysis should complement analyses being done by each partner. To protect confidential information, no data or analysis will be shared across companies.

Further work will be done to ensure the statistical analysis of fuel cell stack degradation is robust and easy to conduct on multiple vehicles and manufacturers automatically. Scripts will be written to summarize data automatically not only for one vehicle (as is currently the capability), but also for compiling and conveying aggregate data results for many vehicles. This type of comparison across companies will be available only to HSDC authorized individuals.

## 6. Status

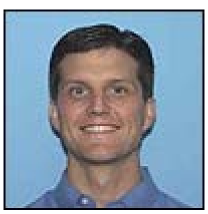
Four cooperative agreements have been awarded to date, as described in Section 3. Initial vehicle data have begun to be been delivered to the HSDC, and the first quarterly validation assessment report has been generated by NREL. However, composite data products will not be published until a sufficient number of data sets from different companies have been received, which will permit protection of confidential data. The project will continue until 2009, at which time it may be extended to validate the 2015 targets.

## 7. Summary

DOE has begun a project titled the "Controlled Hydrogen Fleet and Infrastructure Demonstration and Validation Project." The purpose of this project is to conduct an integrated field validation that simultaneously examines the performance of fuel cell vehicles and the requisite hydrogen infrastructure. The integrated nature of the project enables testing, demonstrating, and validating complete system solutions for hydrogen-powered transportation. Insights from the vehicles and infrastructure will be fed back into DOE's research and development program to guide program structure and to refocus future research, making this project a "learning demonstration."

This paper provides an overview of key objectives and targets of the demonstration and validation project. The partners involved are discussed, and a summary of the data collected and the data collection and analysis process is provided. Finally, examples of specific analyses to be performed during the course of the project are shown. Future papers on this project will elaborate on specific data analyses, provide project status, and begin to report composite data products.

## 8. Author



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13. **SUPPLEMENTARY NOTES**

14. **ABSTRACT** *(Maximum 200 Words)*
In 2003, the U.S. Department of Energy (DOE) initiated the Controlled Hydrogen Fleet and Infrastructure Demonstration and Validation Project, an integrated field validation that simultaneously examines the performance of fuel cell vehicles and the requisite hydrogen infrastructure. Five teams were selected and four cooperative agreements between DOE and industry partners were awarded in fiscal year 2004. The project will continue for 5 years, during which multiple generations of technology will be tested. Technical performance of vehicles and infrastructure will be compared against DOE targets at intermediate stages and at project completion. This paper provides an overview of key objectives and targets of the demonstration and validation project. The partners involved are discussed, and a summary of the data collected and the data collection and analysis process is provided. Finally, examples of specific analyses to be performed during the project are shown.

15. **SUBJECT TERMS**
demonstration; fuel cell; hydrogen; infrastructure; vehicle

| 16. **SECURITY CLASSIFICATION OF:** | | | 17. **LIMITATION OF ABSTRACT** | 18. **NUMBER OF PAGES** | 19a. **NAME OF RESPONSIBLE PERSON** |
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