ON-BOARD DIAGNOSTICS - SECOND GENERATION (OBD-II) SYSTEM CRITERIA FOR ALTERNATE-FUELED VEHICLES

By
Melvin N. Ingalls

FINAL REPORT

Prepared for
ENVIRONMENTAL PROTECTION AGENCY
2565 Plymouth Road
Ann Arbor, Michigan 48105

September 1996

SOUTHWEST RESEARCH INSTITUTE
SAN ANTONIO
HOUSTON
DETROIT
WASHINGTON, DC
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Approved by:

Charles T. Hare, Director
Department of Emissions Research
Automotive Products and Emissions Research Division
FOREWORD

The project effort covered in this final task report was conducted by Southwest Research Institute for the Environmental Protection Agency under Work Assignment No. 1-01, "On Board Diagnostics - Second Generation (OBD-II) System Criteria for Alternate Fueled Vehicles," of Contract 68-C4-0042. The SwRI Revised Work Plan for this Work Assignment was dated May 3, 1996.

Work was begun on May 23, 1996, and completed on September 30, 1996. All work on the project was done within the SwRI Department of Emissions Research. The SwRI Project Leader was Melvin N. Ingalls, and the SwRI Project Number was 08-6886-811.
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<td>Hydrocarbon Efficiency as a Function of GM Oxygen Sensor Index</td>
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<td>Bosch Misfire System</td>
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<tr>
<td>Table</td>
<td>Description</td>
<td>Page</td>
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<td>4</td>
<td>Comparison of Federal OBD and California OBDII Regulations</td>
<td>7</td>
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</table>
EXECUTIVE SUMMARY

On-board diagnostics (OBD) are required by Federal and California regulations to monitor systems which affect emission levels. These regulations require sensors, hardware, and diagnostic algorithms that have not been installed on automobiles in the past. Concurrent with the introduction of OBD, the Federal government is encouraging (and in some cases requiring) the introduction of vehicles that use alternate fuels.

The first objective of this work assignment is to provide EPA with an assessment of the ability of current Federal OBD and California OBD-II systems to function on alternate fuel vehicles. A second objective is to define any areas where currently available systems and procedures are not sufficient for alternate fuel vehicles to meet Federal OBD requirements.

To meet the objectives given above, the project was divided into four tasks: (1) study, and become familiar with, present Federal OBD regulations and future plans; (2) research and compile information on current OBD systems and on alternate fuel systems; (3) using information from the first two tasks, assess OBD capability on alternate fueled vehicles; and (4) specify OBD development needs for alternate fuel vehicles.

While this work assignment was to investigate alternate fuel vehicles in relationship to Federal OBD requirements, California requirements cannot be completely ignored since it is likely that a large fraction of alternate fuel vehicle sales will be in California. Also, through the 1998 model year, compliance with California OBD-II regulations will satisfy Federal OBD requirements.

The EPA requirements for OBD are listed in the Code of Federal Regulations, Title 40 (40CFR). The main reference is in paragraph 86.0xx-17, where "xx" is the model year to which the paragraph applies. Under the provision of subparagraph 86.094-17(i), through the 1998 model year, manufacturers of alternate fuel vehicles can request waivers of specific monitoring requirements for which monitoring may not be reliable using an alternate fuel.

The California requirements are contained in Title 13 California Code of Regulations, Section 1968.1, “Malfunction and Diagnostic Requirements -- 1994 and Subsequent Model-Year Passenger Cars, Light-Duty Trucks, and Medium-Duty Vehicles and Engines.” For alternate fuels, the requirements of this section took effect in 1996, with waivers for specific requirements possible until 1999. A summary of the OBD thresholds for the major emissions-related systems from 40CFR 86.094-17 is shown in the table below.
EMISSIONS THRESHOLDS FOR FEDERAL OBD REGULATIONS
Current Criteria

<table>
<thead>
<tr>
<th>Item</th>
<th>Components</th>
<th>HC</th>
<th>CO</th>
<th>NOx</th>
<th>Comments a</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Catalyst monitor</td>
<td>total exceeds 0.6 g/mi exhaust and exhaust emissions increase 0.4 g/mi over baseline emissions</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Engine misfire</td>
<td>0.4 g/mi</td>
<td>3.4 g/mi</td>
<td>1.0 g/mi</td>
<td>increase in exhaust emissions over baseline</td>
</tr>
<tr>
<td>3</td>
<td>Oxygen sensor monitor</td>
<td>0.2 g/mi</td>
<td>1.7 g/mi</td>
<td>0.5 g/mi</td>
<td>increase in exhaust emissions over baseline</td>
</tr>
<tr>
<td>4</td>
<td>Powertrain-EGR monitor</td>
<td>0.2 g/mi</td>
<td>1.7 g/mi</td>
<td>0.5 g/mi</td>
<td>increase in exhaust emissions over baseline</td>
</tr>
<tr>
<td>5</td>
<td>Powertrain-Secondary air system</td>
<td>0.2 g/mi</td>
<td>1.7 g/mi</td>
<td>0.5 g/mi</td>
<td>increase in exhaust emissions over baseline</td>
</tr>
<tr>
<td>6</td>
<td>Powertrain-Fuel system (trim)</td>
<td>0.2 g/mi</td>
<td>1.7 g/mi</td>
<td>0.5 g/mi</td>
<td>increase in exhaust emissions over baseline</td>
</tr>
<tr>
<td>7</td>
<td>Powertrain-idle air control</td>
<td>0.2 g/mi</td>
<td>1.7 g/mi</td>
<td>0.5 g/mi</td>
<td>increase in exhaust emissions over baseline</td>
</tr>
<tr>
<td>8</td>
<td>Evap system monitor</td>
<td></td>
<td></td>
<td></td>
<td>If evap emissions exceed 30 g/test over 24 hr. diurnal, must detect 0.04 in. orifice leak</td>
</tr>
<tr>
<td>9</td>
<td>Any other powertrain component monitored by manufacturer</td>
<td>0.2g/mi</td>
<td>1.7 g/mi</td>
<td>0.5 g/mi</td>
<td>increase in exhaust emissions over baseline</td>
</tr>
</tbody>
</table>

a If manufacturer chooses not to monitor listed component, then manufacturer must demonstrate emission criteria are not exceeded when malfunction or deterioration occurs.

The majority of alternate gaseous fuel vehicles in service today are conversions of gasoline vehicles, not OEM factory-built vehicles. Thus, while not part of the OBD requirements, the Federal standards for aftermarket conversions are an important part of the discussion of the ability of alternate fuel vehicles to meet OBD requirements. In 1974, EPA issued Mobile Source Enforcement Memorandum No. 1A, which stated the agency’s interim policy on enforcing the tampering provision of the Clean Air Act and provided guidance for aftermarket converters. Recently EPA published a voluntary rule for Aftermarket Conversions. The main CFR section affecting aftermarket conversions was a new subpart F added to 40CFR Part 85, titled “Exemption of Aftermarket Conversions from Tampering Prohibition.” It is very important to note that subpart F is optional, and took effect upon its publication in the Federal Register. Vehicles can still be converted under Memorandum No. 1A.

To assess the ability of current OBD systems to function on alternate fuel vehicles, it is necessary to know what OBD techniques and processes are used in current production vehicles, and what techniques and processes might possibly be used in the future. It was not
the intent of this report to provide a comprehensive explanation of each OBD system, rather, the basic measurement principle was covered to the extent necessary to determine if differences in fuel type and/or fuel control systems could cause difficulty with the use of the technology. For this study, the nine systems listed in the table above were used as the basis for investigating current OBD technology. A literature search was conducted to define the technologies currently in use. A description of the OBD monitoring technique for each of the nine systems is contained in this report.

For purposes of this study, four alternate fuels, for which there are currently light-duty vehicles in production, were considered. These fuels were:

- methanol (as M85: 85% methanol and 15% gasoline)
- ethanol (as E85: 85% denatured ethanol and 15% gasoline)
- CNG (compressed natural gas)
- LPG (liquefied petroleum gas, sometimes referred to as "propane").

There are three types of alternate fuel vehicles: (1) dedicated, (2) flexible fuel, and (3) bi-fuel. Dedicated vehicles use only one fuel, for example, natural gas. Flexible fuel vehicles (FFV) are liquid fuel vehicles and can burn any volumetric combination of gasoline and either M85 or E85 (but not both). Bi-fuel vehicles use two different fuels, but only one fuel at a time. Bi-fuel vehicles generally use gasoline and either CNG or LPG.

In order to determine if current OBD systems are useable on alternate fuel vehicles, it was necessary to understand the differences between alternate fuel vehicle systems and current gasoline vehicle systems. The use of alternate fuels involves changes mainly in the fuel system hardware, the fuel and engine control, and possibly the exhaust aftertreatment system. For each alternate fuel, the fuel system, fuel control, and catalyst systems currently used in alternate fuel vehicles are discussed in the report.

There were four OBD areas that were determined to be affected by the type of fuel. These areas are:

- Catalyst monitoring
- Fuel system trim
- Idle air control
- Evaporative system monitoring.

Of these four areas, it was determined that further OBD system development was needed for alternate fuel vehicles in the area of catalyst monitoring. The developments needed in catalyst monitoring are generic to gasoline as well as alternate fuels. Manufacturers are still conducting development work to reliably apply the dual oxygen sensor approach to vehicles planned to be certified under LEV and ULEV emission standards. The other approaches to catalyst monitoring include determination of the catalyst exotherm with temperature sensors which is still very much in the development stage, and the direct measurement of exhaust oxygen and hydrocarbons concentrations, which are still in the exploratory stage.

For alcohol FFVs, further development is needed to provide an OBD system for the fuel composition sensor. Combustion parameters, however, do change with fuel composition. It is expected, therefore, that a technique to monitor the fuel composition sensor could be
found with moderate effort. Thus, this needed development is not expected to be a long term problem for OBD compliance of FFVs.

Aftermarket conversions (the majority of gaseous fuel vehicles are conversions) have a particularly great need for further OBD system development. The CNG and LPG industry press (magazines, newsletters, and the like) identify OBD-II as the biggest problem facing vehicle conversion companies. There are two general tasks facing the conversion industry: (1) providing OBD for the equipment they install, and (2) ensuring that disabling OEM systems will not cause the MIL to be illuminated. Most of the technical needs of the conversion industry center around either developing their own sophisticated controller or having some access to the OEM controller. OEM companies, however, regard the engine control system and algorithms as proprietary, and in general, will not provide sufficient information to interface with their controls.

The solution to the needs associated with gaseous fuel conversion vehicles meeting the OBD requirements are as much economic as technical in nature, however. Conversion companies, because of the limited capital that can be generated by the relatively small volume of vehicles currently being sold, may find it almost impossible to develop independent systems to meet all of the OBD requirements.
I. INTRODUCTION

On-board diagnostics (OBD) are required by Federal and California regulations to monitor systems which affect emission levels. These regulations require sensors, hardware, and diagnostic algorithms that have not been installed on automobiles in the past. Concurrent with the introduction of OBD, the Federal government is encouraging (and in some cases requiring) the introduction of vehicles that use alternate fuels (that is, a fuel other than gasoline or diesel).

A. Background

With the introduction of electronic feedback controls in the late 1970's, the electronic controller introduced into the automobile a step change in complexity and sophistication. To cope with this increase in sophistication, in the 1980's, vehicle manufacturers began using spare capacity of the electronic engine controller to monitor sensors and systems, and store information on malfunctioning components in the controller for readout by a service technician. Because the checks were all conducted by the vehicle controller, these system checks became known as “on-board diagnostics.”

Research by EPA and the California Air Resources Board (CARB), as part of its effort to further improve the air quality in the state of California, found that the on-board diagnostic approach provided better detection, diagnosis, and repair of malfunctions than did relying on checks during vehicle servicing. Thus in 1985, CARB adopted regulations, starting in the 1988 model year and with full implementation by 1991, for an on-board diagnostic system intended to notify vehicle operators of possible malfunctions of the vehicle emission control systems. This regulation was applicable only to gasoline vehicles, and later become known as OBD-I. In 1989, additional on-board diagnostic requirements were adopted, to be implemented in the 1994 model year. These additional requirements, known as OBD-II, applied to alternate fuel vehicles as well as gasoline fuel vehicles. The Clean Air Act Amendments of 1990 included an OBD program at the Federal level beginning with 1994 model year vehicles. The Federal OBD program was also applicable to alternate fuel vehicles. In March, 1995, an EPA Direct Final Rule was published permitting gaseous alternate fuel vehicles to meet the OBD regulation to the extent possible, but delaying full compliance until the 1999 model year.

At the same time that OBD benefits were being recognized and required, there was a growing awareness that fuels other than gasoline had the possibility of lessening our dependence on foreign petroleum, and providing vehicle exhaust that was less reactive in the atmosphere, thus producing less ozone. Federal laws, particularly the Alternate Motor Fuels Act of 1988, the Clean Air Act Amendments of 1990, and the Energy Policy Act of 1992 (EPACT), provided both incentives and requirements for the use of alternate fuel vehicles. In response to these Federal laws, more and more alternate fuel vehicles will become part of the in-use vehicle fleet over the next few years.

As these alternate fuel vehicles become a larger part of the in-use vehicle fleet, it is important that they have the same level of OBD compliance as current gasoline vehicles. To support EPA efforts for compliance with Federal OBD requirements, information needed to be gathered concerning OBD monitoring on alternate fuel vehicles. The information obtained would be a subset of the total information EPA will use to assess if alternate fuel vehicles
can be in full compliance with OBD monitoring and applicable OBD criteria within the regulatory time frame. The purpose of this project is to supply that information.

B. Objective

The first objective of this work assignment is to provide EPA with an assessment of the ability of current Federal OBD and California OBD-II systems to function on alternate fuel vehicles. A second objective is to define any areas where currently available systems and procedures are not sufficient for alternate fuel vehicles to meet Federal OBD requirements.

C. Approach

To meet the objectives given above, the project was divided into four tasks: (1) study, and become familiar with, present Federal OBD regulations and future plans; (2) research and compile information on current OBD systems and on alternate fuel systems; (3) using information from the first two tasks, assess OBD capability on alternate fueled vehicles; and (4) specify OBD development needs for alternate fuel vehicles.

The first task was accomplished by obtaining copies of the applicable Federal and California regulations, and becoming familiar with their contents. In this work, the worldwide web sites for CARB, the EPA Office of Mobile Sources, and the Government Printing Office were invaluable aids. Future plans were discussed with EPA and CARB personnel involved with OBD regulations. The second task involved gathering information using literature searches, telephone contacts with government and industry personnel, and search of the Internet World Wide Web for information from government, trade organizations, and companies.

The last two tasks involved an engineering analysis of the data obtained to determine how current gasoline OBD technology could be applied to alternate fuel vehicles, and to determine if there were specific OBD areas where current gasoline technology could not be applied. The results of these tasks are presented in the report sections that follow, with a separate section for each task.
II. FEDERAL AND CALIFORNIA OBD REQUIREMENTS

While the requirements of this work assignment are to investigate alternate fuel vehicles in relationship to Federal OBD requirements, California requirements cannot be completely ignored, since it is likely that a large fraction of alternate fuel vehicle sales will be in California. Also, through the 1998 model year, compliance with California OBD-II regulations will satisfy Federal OBD requirements. Thus, some familiarity with CARB OBD-II regulations is required. EPA and CARB requirements will be discussed separately in the paragraphs below.

A. Federal OBD Requirements

The EPA requirements for OBD are listed in the Code of Federal Regulations, Title 40 (40CFR). The main reference is in paragraph 86.0xx-17, where "xx" is the model year to which the paragraph applies. A complete list of the current CFR paragraphs referring to OBD is presented in Table 1, in the format 86.0xx-yy, where “xx” is the model year and “yy” is the topic.

From paragraph 86.094-17, the systems requiring monitoring, and the limits permitted before lighting the Malfunction Indicator Light (MIL), are summarized in Table 2. As shown in that table, there are nine systems or areas that are subject to OBD monitoring. For future requirements, as far as can be ascertained, the only difference in paragraph 86.094-17 (applicable to 1994 and subsequent years) and paragraph 86.098-17 (applicable to 1996 and subsequent years) is the addition of a refueling system requirement for evaporative systems.

The provisions of subparagraph 86.094-17(a), which lists systems and limits of Items 1 to 8 in Table 2, do not apply to natural gas vehicles until 1998. However, subparagraph 86.094-17(b) requires the monitoring, for continuity or functionality, of the evaporative emission purge control, the catalyst, oxygen sensor, detection of misfiring cylinders, and the circuit continuity of all computer connections for all non-diesel vehicles starting in 1994.

Under the provision of subparagraph 86.094-17(i), through the 1998 model year, manufacturers of alternate fuel vehicles can request waivers of specific monitoring requirements for which monitoring may not be reliable using an alternate fuel. The other paragraphs listed in Table 1 refer to OBD systems, but do not add to the system requirements.

B. California Requirements

The California requirements are contained in Title 13 California Code of Regulations, Section 1968.1, “Malfunction and Diagnostic Requirements -- 1994 and Subsequent Model-Year Passenger Cars, Light-Duty Trucks, and Medium-Duty Vehicles and Engines.” For alternate fuels, the requirements of this section took effect in 1996, with waivers for specific requirements possible until 1999. The California criteria for lighting the MIL are different from the Federal requirements given in Table 2. In the future, California will require that the MIL be lighted whenever HC, CO, or NOx emission levels exceed 1.5 times the FTP standard.
### TABLE 1. LIST OF CFR PARAGRAPHS CONCERNING OBD

<table>
<thead>
<tr>
<th>&quot;-yy&quot; (topic)</th>
<th>Title</th>
<th>&quot;xx&quot; (applicable model year)</th>
<th>94</th>
<th>95</th>
<th>96</th>
<th>98</th>
</tr>
</thead>
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<tr>
<td>-17</td>
<td>Emission Control Diagnostic System</td>
<td>✓</td>
<td>NA</td>
<td>NA</td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>-18</td>
<td>---</td>
<td>(has been remanded by the courts)</td>
<td></td>
<td></td>
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<tr>
<td>-21</td>
<td>Application for Certification</td>
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<td>NA</td>
<td>✓</td>
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<td>-25</td>
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<td>✓</td>
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<tr>
<td>-35</td>
<td>Labeling</td>
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<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
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</tbody>
</table>

### TABLE 2. EMISSION THRESHOLDS FOR FEDERAL OBD REGULATIONS

**Current Criteria**

<table>
<thead>
<tr>
<th>Item</th>
<th>Components</th>
<th>HC</th>
<th>CO</th>
<th>NOₓ</th>
<th>Comments</th>
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<tbody>
<tr>
<td>1</td>
<td>Catalyst monitor</td>
<td>total exceeds 0.6 g/mi exhaust and exhaust emissions increase 0.4 g/mi over baseline emissions</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Engine misfire</td>
<td>0.4 g/mi</td>
<td>3.4 g/mi</td>
<td>1.0 g/mi</td>
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<td>3</td>
<td>Oxygen sensor monitor</td>
<td>0.2 g/mi</td>
<td>1.7 g/mi</td>
<td>0.5 g/mi</td>
<td>increase in exhaust emissions over baseline</td>
</tr>
<tr>
<td>4</td>
<td>Powertrain-EGR monitor</td>
<td>0.2 g/mi</td>
<td>1.7 g/mi</td>
<td>0.5 g/mi</td>
<td>increase in exhaust emissions over baseline</td>
</tr>
<tr>
<td>5</td>
<td>Powertrain-Secondary air system</td>
<td>0.2 g/mi</td>
<td>1.7 g/mi</td>
<td>0.5 g/mi</td>
<td>increase in exhaust emissions over baseline</td>
</tr>
<tr>
<td>6</td>
<td>Powertrain-Fuel system (trim)</td>
<td>0.2 g/mi</td>
<td>1.7 g/mi</td>
<td>0.5 g/mi</td>
<td>increase in exhaust emissions over baseline</td>
</tr>
<tr>
<td>7</td>
<td>Powertrain-idle air control</td>
<td>0.2 g/mi</td>
<td>1.7 g/mi</td>
<td>0.5 g/mi</td>
<td>increase in exhaust emissions over baseline</td>
</tr>
<tr>
<td>8</td>
<td>Evap system monitor</td>
<td></td>
<td></td>
<td></td>
<td>If evap emissions exceed 30 g/mi over 24 hr. diurnal, must detect 0.04 in. office leak</td>
</tr>
<tr>
<td>9</td>
<td>Any other powertrain component monitored by manufacturer</td>
<td>0.2 g/mi</td>
<td>1.7 g/mi</td>
<td>0.5 g/mi</td>
<td>increase in exhaust emissions over baseline</td>
</tr>
</tbody>
</table>

*a* If manufacturer chooses not to monitor listed component, then manufacturer must demonstrate emission criteria are not exceeded when malfunction or deterioration occurs.
A presentation by CARB for an SAE TOPTEC meeting on OBD-II requirements held in San Diego on August 9-11, 1994, contained a comparison of CARB and EPA OBD requirements. This comparison is shown in Table 3. The implication of the comparison is that CARB requirements are much more complete than EPA requirements. A comparison on a paragraph-by-paragraph basis, done for this study, indicates that the items required to be monitored are very similar. This comparison is given in Table 4.

While some of the systems listed in the "Federal Requirements" column of Table 4 are not specifically named in the CFR, these systems are covered under paragraph 86.094-17(a), since their malfunction would be expected to cause emissions increases greater than permitted by that paragraph.

C. **Federal Standards and Certification Procedures for Aftermarket Conversions**

The majority of alternate gaseous fuel vehicles in service today are conversions of gasoline vehicles, not OEM factory-built vehicles. Thus, while not part of the OBD requirements, the Federal standards for aftermarket conversions are an important part of the discussion of the ability of alternate fuel vehicles to meet OBD requirements.

In 1974 the EPA issued Mobile Source Enforcement Memorandum No. 1A, which stated the agency's interim policy on enforcing the tampering provision of the Clean Air Act. This memorandum stated, in effect, that conversion to an alternate fuel would not be considered tampering if the installer had a reasonable basis for knowing that such modifications would not adversely affect emissions performance. In March 1993, EPA issued a fact sheet stating that "reasonable basis" may include certification of the conversion system by CARB or by the Colorado Department of Health.

On September 21, 1994, EPA published in the Federal Register the Final Rule for "Standards for Emissions From Natural Gas-Fueled, and Liquefied Petroleum Gas-Fueled Motor Vehicles and Motor Vehicle Engines and Certification Procedures for Aftermarket Conversions." This final rule affected 40CFR Parts 80, 85, 86, and 600, and included 125 additions and changes to the CFR. The main CFR section affecting aftermarket conversions was a new subpart F added to 40CFR Part 85, titled "Exemption of Aftermarket Conversions from Tampering Prohibition." It is very important to note that the procedure in subpart F is optional, and took effect upon the publication in the Federal Register. Vehicles can still be converted under Memorandum No. 1A.

Subsection F of 40 CFR Part 85 contains three important definitions. To paraphrase these definitions, an "aftermarket conversion system" is the collection of hardware installed on the vehicle or engine which allows the vehicle to operate on a fuel other than the fuel for which the vehicle was manufactured, and which affects the emissions performance of the converted vehicle. An "aftermarket conversion certifier" is the company which assembles the aftermarket conversion system, and certifies the system. An "aftermarket conversion installer" is the company or individual which installs the aftermarket conversion system on a vehicle. Note that the "installer" does not have to be a "certifier," and vice-versa.

To receive an exemption from the tampering prohibitions of the Clean Air Act, an "aftermarket conversion certifier" must certify the aftermarket conversion system under 40CFR Part 86, and accept liability for in-use performance of the system. To receive the same exemption, an "aftermarket conversion installer" must install a certified aftermarket conversion system, and also accept liability for in-use performance of the system.
<table>
<thead>
<tr>
<th><strong>On-Board Diagnostics</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Comparison of OBD II and Federal OBD</strong></td>
</tr>
</tbody>
</table>

- **OBD II**
  - Requires monitoring of all emission-related components
  - Malfunctions indicated before emissions exceed 1.5 times any of the emission standards

- **Federal OBD**
  - Required monitoring limited to catalyst, misfire, and oxygen sensor
  - Other systems monitored if malfunction causes emissions to exceed a fixed emission threshold
# Table 4. Comparison of Federal OBD and California OBD-II Regulations

<table>
<thead>
<tr>
<th>Federal Regulations (40 CFR 86.094-17)</th>
<th>California Regulations (Title 13 CFR section 1968.1)</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Catalyst deterioration (a)(1) and (b)(2)</td>
<td>catalyst performance (b)(1.0)</td>
<td>hydrocarbons only</td>
</tr>
<tr>
<td>Engine misfire (a)(2) and (b)(2)</td>
<td>engine misfire (b)(3.0)</td>
<td></td>
</tr>
<tr>
<td>Oxygen sensor deterioration (a)(3) and (b)(2)</td>
<td>oxygen sensor (b)(8.0)</td>
<td>Fed: increase in NOx and CO CA: voltage and rate</td>
</tr>
<tr>
<td>Fuel System (under other emission-related powertrain components) (a)(4)</td>
<td>Fuel system (b)(7.0)</td>
<td></td>
</tr>
<tr>
<td>EGR system (under other emission-related powertrain components) (a)(4)</td>
<td>EGR system (b)(9.0)</td>
<td></td>
</tr>
<tr>
<td>Secondary Air (under other emission-related powertrain components) (a)(4)</td>
<td>Secondary Air (b)(5.0)</td>
<td></td>
</tr>
<tr>
<td>Evaporative emissions leak (a)(4) electronic purge control (b)(1)</td>
<td>evaporative emissions (b)(4.0)</td>
<td></td>
</tr>
<tr>
<td>Computer circuit continuity (b)(1)</td>
<td>Electronic input components Electronic output components (b)(10)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Catalyst heating (b)(2.0)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Engine coolant sensor (proposed)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>PCV system (proposed)</td>
<td></td>
</tr>
</tbody>
</table>

Numbers in parentheses refer to subparagraphs of Federal and California regulations.

A supplemental emission control information label must be installed on each converted vehicle. The label must show the vehicle model year; the aftermarket conversion certifier’s name, address, and telephone number; the installer’s name, address, and telephone number; the date on which the aftermarket conversion system was installed; and the mileage of the vehicle at the time of conversion.
III. CURRENT AND FUTURE OBD SYSTEMS

To assess the ability of current OBD systems to function on alternate fuel vehicles, it is necessary to know what OBD techniques and processes are used in current production vehicles, and what techniques and processes might possibly be used in the future. For this study, the nine systems listed in Table 2 were used as the basis for determining current OBD technology.

It is not the intent of this report to provide a comprehensive explanation of each OBD system, rather, the basic measurement principle will be covered to the extent necessary to determine if differences in fuel type and/or fuel control systems could cause problems with the use of the technology. Each system will be discussed separately in the paragraphs below.

A. Catalyst Monitor

While the method for catalyst monitoring is not specifically required by the California regulations in Section 1968.1, all current systems use two oxygen sensors, one on the upstream and one on the downstream side of the catalyst, to meet the CARB OBD-II catalyst HC efficiency requirements. Since Federal regulations do not specify a methodology either, manufacturers use this dual oxygen sensor method for both California and 49 state cars.

As the name implies, the dual oxygen sensor method uses two oxygen sensors, one before and one after the catalyst. Because of the oxygen storage property of current catalysts, the two oxygen sensor signals will differ in some way such as amplitude, frequency, or phase. There are a number of different algorithms, either in-use or proposed, to quantify oxygen storage from these parameters. Figure 1 illustrates the basic concept. For OBD, hydrocarbon conversion efficiency is then inferred from the determination of oxygen storage.

The dual oxygen sensor method, as currently used, actually measures oxygen storage and not catalyst efficiency. Oxygen storage is a function of the amount and state of cerium in the catalyst, so that there can be catalysts that have no oxygen storage, yet are still efficient at reducing HC. Nevertheless, with current technology catalysts, efficiency tends to track oxygen storage. Thus, development efforts continue toward perfecting the dual sensor technique, and applying it to LEV and ULEV emission levels. There were a number of production vehicles that used the two oxygen sensor method to meet California OBD-II requirements for 1994 and 1995. In those years the MIL was required to light when catalyst HC efficiency fell below 60 percent.

In a conversation with Allen Lyons of CARB, he mentioned that CARB still believes that the dual oxygen sensor method will fulfill OBD requirements for vehicles meeting LEV and ULEV standards, and that one manufacturer is using dual oxygen sensors for ULEV.\(^4\) Several SAE papers, however, present data that indicate that this method cannot reliably detect the small efficiency changes in the highly efficient catalysts that will be necessary for ULEVs.\(^5,6,7,8\)

The problem at high catalyst efficiencies is illustrated graphically in two SAE papers. Figure 2, from Reference 5, shows oxygen storage capacity (OSC) as a function of catalyst HC efficiency. Figure 3, from Reference 7, shows catalyst HC efficiency as a function of a GM \(O_2\) Sensor Index (the sensor index is based on a proprietary algorithm that produces a
Dual O2 Sensor Method

On Board Diagnostics TOPTEC

FIGURE 1. CONCEPT FOR TWO OXYGEN SENSOR METHODS OF CATALYST EFFICIENCY
(Source: On-Board Diagnostics (OBD) Update TOPTEC, Aug. 9-11, 1994)
FIGURE 2. OXYGEN STORAGE CAPACITY AS A FUNCTION OF HYDROCARBON EFFICIENCY
(Source: SAE Paper 920831)

FIGURE 3. HYDROCARBON EFFICIENCY AS A FUNCTION OF GM OXYGEN SENSOR INDEX
(Source: SAE Paper 932666)
numerical quantity proportional to oxygen sensor activity). The GM sensor index is constructed in such a manner that the lower the number, the better the oxygen storage. Both these graphs show the difficulty with meeting the California requirement of identifying an emission increase of 1.5 times the FTP emission rate at the high (>95%) HC efficiencies required to meet LEV and ULEV standards, since at efficiencies greater than 95 percent, there appears to be little correlation between efficiency and oxygen storage. It is important to note that these references are now several years old, and that more recent developments in OBD technology and catalyst systems are resolving these difficulties.

There are other possibilities for determining catalyst efficiency. Several SAE papers discuss measuring the catalyst exotherm as a means of determining efficiency.\(^{(9,10,11,12,13)}\) At this time, however, none of these systems are in production vehicles.

**B. Engine Misfire**

Currently, most manufacturers use crankshaft speed variations to detect engine misfire. References 14 and 15 describe this method as applied to a Volvo 850 and a Nissan 3.0 liter V6 engine, respectively. This method, however, can give a false misfire indication on rough roads without proper filtering.

Misfire detection from crankshaft speed fluctuations derives from the fundamental relationship for engine torque given below.\(^{(16)}\)

\[ M = W + J + \omega \frac{d\omega}{dt} \]

Where:

- \( M \) = Engine torque
- \( W \) = Load torque
- \( J \) = Moment of inertia
- \( \omega \) = Angular speed of the engine

To detect a misfiring cylinder, the torque (\( M \)) of each cylinder is evaluated by measuring the time between two successive ignition events. This gives a measure of the mean value of the speed during that angular segment. A change of the engine torque (\( M \)) results in a corresponding change in the engine speed (\( d\omega/dt \)). The speed is also influenced by the load torque (\( W \)). To account for changes that are not due to misfire, sources of engine load changes must be included in the basic engine calibration data. Typically, these engine load changes include road surface conditions, engine temperature differences, and various engine transients.

Figure 4 shows the main elements of the Bosch misfire detection system that is used on the Volvo 850.\(^{(7)}\) The engine speed is obtained from the crankshaft sensor which counts the notches on the flywheel or other disk mounted on the crankshaft. This counting is the main input into the powertrain control module. For misfire detection, the flywheel is split into as many sectors as there are engine cylinders. As the flywheel sensor measures the rotation of the crankshaft, it can also sense a disturbance from the engine block to which the sensor is bolted, if the engine is rocked by an external load such as a road bump. An accelerometer is included in the system to measure these external loads.
Powertrain Control Module

FIGURE 4. BOSCH MISFIRE SYSTEM
(Source: Adapted from SAE Paper 932665)
An alternate method found in the literature is to use spark plug ion-gap sensing.\(^{(17)}\) Ion gap sensing is based on the application of a low voltage, positive DC bias to the spark plug immediately after ignition coil discharge. The result is an instantaneous ion current directly proportional to the number of combustion ions in the cylinder. The bias is applied only during the time in the cycle when combustion is supposed to be taking place. The ion current during this time period has a complex wave shape. At present, this technology can only be used with ignition systems that have one coil per spark plug. For misfire detection, ion current level and duration can be used to define misfire over a wide range of speeds and loads.

C. **Oxygen Sensor Monitor**

Most oxygen sensors on current model cars are electrically heated, and future LEV and ULEV oxygen sensors will probably all be electrically heated. In addition to the oxygen sensors in or near the exhaust manifold that provide the signal for the engine fuel control, the sensors downstream of the catalyst, used to determine catalyst efficiency, must also be checked for proper operation.

Generally three checks are made on the oxygen sensors:\(^{(18)}\) (1) a heat-up test, (2) response time test, and (3) a sensor voltage test. For the heat-up test, the time to activity (rich-to-lean and lean-to-rich switching) during a cold start can be measured and compared to a maximum allowable time stored in the control system computer. If the heating time exceeds the maximum allowable time, the test is considered to have failed.

Response time is measured after the sensor has warmed up. The output of an oxygen sensor is above 600 mV when the exhaust gas is rich, and below 300 mV when the exhaust is lean. The response time test can look at the time it takes to shift from rich-to-lean (or lean-to-rich), and compare this time to the maximum allowable time stored in the computer. It may be necessary to use the fuel control to initiate an A/F shift in the engine to measure the oxygen sensor response. This is particularly true for the oxygen sensor downstream of the catalyst, since with a properly operating catalyst and good fuel control, this sensor should show little change in output.

The sensor voltage test checks for shorts to voltage (generally about one volt) and shorts to ground (less than 100 mV). The voltage test also checks that the sensor exceeds rich and lean threshold voltages stored in the computer.

D. **EGR Monitor**

There are a number of ways to monitor EGR. GM uses a change in manifold air pressure (MAP) when the EGR valve is opened or closed (depending on when the test is performed) to determine if the EGR valve is working.\(^{(18)}\) Volvo uses a temperature sensor mounted in the EGR line to determine if there is a flow of exhaust gas.\(^{(7)}\) In one of their new engines, Nissan uses a temperature sensor to detect when EGR is in operation.\(^{(15)}\)

E. **Secondary Air System**

According to CARB, failure of current technology (non-LEV) secondary air systems do not cause either the Federal or California limits to be exceeded.\(^{(19)}\) For California, this means that only a functional check is necessary. If a secondary air system is used at all, it
is used during the first minute or two of the cold start. Unlike secondary air systems that were used with oxidation catalysts in the seventies, employing belt driven air pumps that were continuously “on,” current systems use electric pumps that are turned on and off by the engine control system. There are several tests that can be made to ensure the secondary air system is working. Almost all systems infer secondary air system operation by oxygen sensor voltage shifts when the air pump turns on and off. Some systems even purposely turn the pump on momentarily during closed loop operation to check the oxygen sensor shifts. There are no systems that use flow meters in the secondary air stream.(19)

F. **Fuel System (Trim)**

To maintain three-way control, all current technology gasoline engines use an oxygen sensor feedback system. Most engine controls also measure engine inlet air flow. Fuel control can be either open loop or closed loop. During open loop control, the timing and amount of fuel injected are determined by the engine electronic control system from measurements of engine speed and inlet air, or by an estimate of inlet air flow by the speed-density method if air flow is not actually measured. Throttle position is often an additional input to the control. Closed loop control uses the exhaust gas oxygen sensor to provide a feedback trim to the basic open loop fuel injector parameters. Controls are currently so sophisticated that both a long term and a short term trim can be determined from the oxygen sensor. There is generally some limit to the amount of trim that is permitted by the oxygen sensor. For OBD systems, this fuel trim must be checked for proper operation.

There are probably as many different techniques for checking the fuel system trim as there are different fueling and fuel control systems. All systems appear to have complex checks, generally checking that one or more (usually more) signals do not exceed some predetermined allowable limit stored in the computer.

The GM fuel trim diagnostic, for instance, monitors the averages of long-term and short-term fuel trim. These fuel trim values are based primarily on the oxygen sensor output, but are processed by the Powertrain Control Module (the on-board control module that monitors engine functions), using other inputs to provide a ± 100 percent scale for output. If these fuel trim values reach and stay at their maximum for a period of time, a malfunction is indicated. However, a complex system of weighting factors, depending on speed and load, determines how badly the fuel trim malfunction affects the emissions, and whether the MIL should be illuminated.(18) Current gasoline fuel system trim OBD thus relies on an electronic feedback fuel control system, and a control module that has sufficient memory and computational capacity for the complex schemes used.

G. **Idle Air Control**

Idle speed control is generally done with an idle air control (IAC) valve. At closed throttle this valve opens to permit sufficient air flow into the engine to match the programmed idle fuel rate. A drawing of an IAC valve, taken from Reference 20, is shown in Figure 5.

One non-intrusive method to check the operation of the IAC valve is to compare the engine idle speed with the desired idle speed value stored in the computer. Another, more intrusive method, is to actuate the IAC valve at predetermined off-idle conditions, and compare changes in either intake air or MAP (or both) with stored values. GM uses both of
FIGURE 5. SKETCH OF IDLE AIR CONTROL (IAC) VALVE
(from Reference 20)
these techniques to check the operation of IAC valves on GM cars. GM states, however, that it requires careful calibration of the IAC diagnostic system not to adversely affect drivability and emissions when activating the IAC valve for an intrusive check.\(^{(18)}\)

H. **Evaporative System Monitor**

Evaporative system monitoring requires several tests for current systems. Figure 6 is a schematic of a GM evaporative system that is typical of current systems.\(^{(18)}\) The major components of the system are: charcoal canister, purge solenoid, vent solenoid, fuel tank pressure sensor, fuel tank level sensor, and fuel tank cap.

This system differs from older systems in that the canister bottom is not open to the atmosphere, but rather vents to the atmosphere though the vent solenoid valve. This solenoid valve is normally open, so that it also provides the fresh air to purge the canister during the vapor purge cycle. Another addition, when compared to older systems, is the fuel tank pressure sensor, which is a strain gage sensor much like the MAP sensor.

For the GM system, six different diagnostic tests are performed during vehicle operation to meet OBD-II requirements.\(^{(18)}\) These tests are:

- Power up vacuum test
- Excess vacuum test
- Loaded canister test
- Weak vacuum test
- Small leak test
- Purge solenoid leak test

The details of these tests will not be covered here, but their functions will be explained to help appreciate the level of testing required. Both the power up vacuum test and the excess vacuum test are designed to detect restriction or blockage in the vent path. The loaded canister test is designed to test the whole evaporative system for leaks. This test monitors the oxygen sensor for a rich-side response when the purge solenoid valve is opened, indicating that fuel vapor is being drawn into the engine from the canister.

The weak vacuum test and the small leak test are run if the loaded canister test fails. Both the latter two tests use the fuel tank pressure sensor to detect leaks in the evap system; the weak vacuum test, by checking that there is a vacuum in the gas tank when the vent is closed while the purge valve is open, and the small leak test by checking the rate of vacuum decay in the fuel tank when both the vent and purge solenoid valves are closed. The purge solenoid leak test is an active test that is designed to detect a manifold vacuum leak through the purge solenoid. The test commands the vent solenoid and purge solenoid closed when purge is not occurring. If the fuel tank pressure sensor indicates vacuum, the purge solenoid is leaking.

I. **Other Components**

Since the advent of electronic fuel injection systems, manufacturers have realized that the computer was capable of doing some on-board diagnostics. Early systems simply used spare processor time to look at inputs and outputs to see if everything was operating properly, and provide the service technician with some guidance for repair of malfunctioning
FIGURE 6. GM ENHANCED EVAPORATIVE EMISSION SYSTEM
(Source: GM Training Manual 16030.02-1)
systems. This capability has greatly expanded over the years, so that currently there is a long list of components checked by the computer.

Paragraph 86.094-17 of 40CFR requires "...all emission-related powertrain components connected to the computer shall, at a minimum be monitored for continuity..." While the list of components connected to the computer varies from manufacturer to manufacturer, the diagnostic trouble codes have been standardized using SAE Recommended Practice J2012. The list of codes is much too long to be included here, and since only continuity monitoring is required, the functioning of these components will not investigated in this project.
IV. ALTERNATE FUEL SYSTEMS

In order to determine if current OBD systems are useable on alternate fuel vehicles, it is necessary to understand the differences between alternate fuel vehicle systems and current gasoline vehicle systems. This section first defines the alternate fuels considered in this study, then discusses the different types of alternate fuel vehicles and the differences between alternate fuel systems and gasoline systems.

A. Alternate Fuels

A number of publications have long lists of alternate fuels. For purposes of this study, four alternate fuels, for which there are currently light-duty vehicles in production, will be considered. These fuels are:

- methanol (as M85: 85% methanol and 15% gasoline)
- ethanol (as E85: 85% denatured ethanol and 15% gasoline)
- CNG (compressed natural gas)
- LPG (liquefied petroleum gas, sometimes referred to as "propane").

Methanol, ethanol, and sometimes LPG are introduced into the engine in liquid form, while CNG and generally LPG are introduced into the engine in gaseous form. All these fuels can utilize current spark ignition reciprocating engine designs with some modifications. Liquefied natural gas (LNG) is used in heavy-duty alternate fuel applications such as buses, but not usually in light duty vehicles. Thus, LNG will not be considered in this project. Alternate fuels are generally considered to be non-petroleum fuels, therefore, for this report, diesel fuel will not be considered as an alternate fuel. While hydrogen is a non-petroleum fuel, its practical use is too far in the future to be considered in this study.

B. Alternate Fuel Vehicles

There are three types of alternate fuel vehicles: (1) dedicated, (2) flexible fuel, and (3) bi-fuel. Dedicated vehicles use only one fuel, for example, natural gas. Flexible fuel vehicles (FFV) are liquid fuel vehicles and can burn any volumetric combination of gasoline and either M85 or E85 (but not both). Bi-fuel vehicles use two different fuels, but only one fuel at a time. Bi-fuel vehicles generally use gasoline and either CNG or LPG.

Since dedicated vehicles have only one fuel system, meeting OBD requirements is straightforward, though not necessarily easy. Currently all FFV's are OEM designed and built, and this situation is expected to continue for the foreseeable future. Flexible fuel vehicle fuel systems, therefore, have been developed by the vehicle manufacturer, and the engine fuel hardware and control system are essentially the same for both gasoline and whichever alcohol is used. Solutions to the OBD requirements, however, must fit a wider range of fuel properties.

Bi-fuel vehicles have both liquid and gaseous fuels, which requires two separate fuel systems and sets of controls. The separate fuel systems of bi-fuel vehicles may require different solutions to OBD requirements. In addition, for bi-fuel vehicles, the non-operation of one fuel system must not cause the malfunction indicator light (MIL) to illuminate while the other system is in operation.
The use of alternate fuels involves changes mainly in the fuel system hardware, the fuel and engine control, and possibly the exhaust aftertreatment system. For each alternate fuel, the fuel system, fuel control, and catalyst systems currently used in alternate fuel vehicles will be discussed below. Since bi-fuel vehicles may have greater difficulty with OBD requirements, these vehicles will be discussed as a separate category.

1. Dedicated Methanol and Methanol FFVs

In model year 1995, there were two production methanol vehicles offered for sale: the Dodge Intrepid, a dedicated methanol vehicle, and the Ford Taurus FFV. In 1996, only one production methanol vehicle was available: the Ford Taurus FFV. From 1992 to 1995, Ford has sold almost 7500 Taurus FFVs (methanol and ethanol). In 1996 Ford produced approximately 2750 methanol FFVs. These production vehicles are apparently meeting the current need for methanol vehicles, since there are no references in the literature to methanol conversion vehicles, other than for experimental purposes, in the past several years.

a. Fuel System

Figure 7 is a phantom view of a Honda FFV from Reference 24, showing changes from a gasoline vehicle. Most of the changes are in materials or minor modifications to current hardware (such as a revised pressure regulator to allow increased fuel rail pressure, and a heated spark plug with a colder heat range). The only additional hardware in Figure 7 is the alcohol (fuel composition) sensor. Presumably, a dedicated methanol vehicle would not need the fuel composition sensor, and so would have a fuel system that is essentially similar to a gasoline vehicle. The other modifications shown in Figure 7 would apply to a dedicated methanol vehicle as well as an FFV.

The key to the fuel flexibility of the FFV is the fuel composition sensor, which measures the amount of methanol in the system. The fuel sensor sends a signal to the fuel control computer that adjusts the fuel flow and spark timing to the optimum for whatever fuel composition is in the fuel line. There are two common types of fuel composition sensors mentioned in the literature; optical and capacitor. Both produce a voltage proportional to the amount of alcohol in the fuel. Figure 8 is a drawing of an optical type fuel composition sensor from Reference 25.

b. Control system

The fuel control system hardware for a methanol vehicle, dedicated or FFV, is essentially the same as for a gasoline vehicle, except that the FFV has a fuel composition sensor. The control tables of spark timing, injector timing and firing duration are, of course, different for methanol, but the overall fuel control concept and approach is the same for methanol and gasoline. The FFV will have more complex spark and injector algorithms and tables, which will use the input from the fuel composition sensor, so that any combination of gasoline and methanol can be used.

c. Catalyst system

The FFV exhaust aftertreatment system is, of course, the same for gasoline and methanol use. Methanol, however, can cause relatively high emissions of
FIGURE 7. PHANTOM VIEW OF HONDA FFV FUEL SYSTEM
(Source: SAE Paper 922276)
FIGURE 8. DRAWING OF FUEL COMPOSITION SENSOR
(Source: From SAE Paper 910861)
aldehydes during a cold start. In order to meet the California formaldehyde emission standard of 15 mg/mile with M85, one manufacturer found it necessary to add a one liter close-coupled warm-up catalyst on a two liter engine in an developmental FFV. Similar aftertreatment requirements were found by other methanol vehicle research projects.\(^{24,26}\) Thus, it appears that with current technology, a warmup or heated catalyst will be required for methanol vehicles to meet California formaldehyde emission standards.

2. Dedicated Ethanol and Ethanol FFVs

For 1995 and 1996, the Ford Taurus FFV was the only production vehicle available for use with E85. In 1996 Ford produced approximately 2750 ethanol Taurus FFVs.\(^{23}\) For 1997, GM has announced that all its 4 cylinder compact pickup trucks (Chevrolet S-series and GMC Sonoma) will be E85 FFVs.\(^{22}\)

The ethanol FFV Taurus uses the same fuel and fuel control systems as the methanol Taurus FFV. At this time, there is no information available on the GM pickup trucks. In general, however, the remarks in the discussion of methanol vehicles apply as well to ethanol vehicles.

3. Dedicated CNG

In 1995 there were only two OEM models of dedicated CNG vehicles available, both made by Chrysler Corp. These two models were the Chrysler Ram Van/Wagon and the Dodge Caravan/Plymouth Voyager minivan. In 1996 the Dodge Ram and Dodge Dakota pickups and Ford Crown Victoria were added to the dedicated CNG vehicles available. These vehicles all use OEM designed fuel systems. GM halted its CNG vehicle program in 1994. Chrysler has sold about 4000 CNG units since it began offering them in 1992, and has sold about 700 of its 1996 versions. Chrysler has announced that it will not offer any CNG vehicles in 1997\(^{27}\), presumably leaving the Ford Crown Victoria as the only dedicated CNG vehicle available from an OEM. Dedicated CNG vehicles are also available as conversions, with the fuel system hardware and control system installed by a conversion company, or sometimes by end-user fleet maintenance personnel themselves.

a. Fuel System

The fuel system on the Chrysler vehicles uses a multipoint fuel injection system operating at stoichiometric air/fuel ratio. A phantom view of a Dodge van with system components identified is shown in Figure 9, and a phantom view of the Ford Crown Victoria is shown in Figure 10. Ford also uses a multipoint fuel injection system. A schematic of a typical dedicated natural gas multipoint fuel system, taken from Reference 28, is shown in Figure 11.

An example of an aftermarket CNG conversion system with open loop control and a gas induction valve (also called a gas ring or gas mixer) is shown in Figure 12. The system shown is an IMPCO AFE system used in the NREL Clean Fleet program.\(^{29}\)

b. Control system

All the OEM dedicated natural gas vehicles use multipoint fuel injection. Therefore, the control systems can be modifications of the gasoline electronic control system.
FIGURE 9. DODGE VAN NATURAL GAS FUEL SYSTEM COMPONENTS
(Source: SAE Paper 921551)
FIGURE 10. FORD CROWN VICTORIA NATURAL GAS FUEL SYSTEM COMPONENTS
(Source: Ford Sales Literature)
FIGURE 11. SCHEMATIC OF TYPICAL DEDICATED NATURAL GAS FUEL SYSTEM
(Source: SAE Paper 942005)
FIGURE 12. IMPCO OPEN-LOOP CNG FUEL AND CONTROL SYSTEM
(Source: NREL Clean Fleet Final Report: Vol. 2, Project Design and Implementation)
Dedicated CNG conversions, however, use their own fuel controls, and generally do not use multipoint fuel injection, but rather use throttlebody gas induction mixers. Both open-loop and closed-loop control systems are found in recent vehicles. To meet future emission standards, however, control systems will all have to be closed loop. In the past, dedicated conversion systems could use their own stand alone fuel control system. Currently, however, the vehicle engine electronic control unit controls so many functions, including the OBD system, that the OEM system cannot be disabled.

There are two types of aftermarket control systems that do not disable the OEM system: (1) those that “tee off” the input signals to the OEM control, and (2) those that intercept the fuel injector output from the OEM control. Figure 13 shows block diagrams of the two types of systems. The first system intercepts the signals from the various engine sensors going to the OEM controller and uses these signals in an aftermarket controller, together with any signals needed from the aftermarket hardware, to control the fuel flow. The IMPCO AFE system shown in Figure 12 uses this type of control system. The second type intercepts the OEM signal to the gasoline fuel injectors, and “translates” it into a signal to the CNG metering device. The Translator™ bi-fuel system developed by SwRI is an example of the second type of system.

c. Catalyst system

References 29 and 31 both report that with Pt/Rh catalysts, NOx and THC conversion efficiency both decrease on the lean side, when using natural gas, to a much greater extent than with gasoline. Using a Pd catalyst improves the situation. Nevertheless, natural gas has a narrower “window” (i.e. the A/F ratio band where high conversion efficiencies are obtained for HC, CO, and NOx). Thus, tighter control of A/F ratio is needed for natural gas catalysts to obtain high conversion rates of all emissions. SwRI tested natural gas catalysts for the Chrysler minivan and reported results in Reference 32. This testing showed the same need for an accurate, narrow A/F window that other studies had shown. For the minivan, Chrysler chose a converter with a Pt/Rh front brick and a Pd-only rear brick.

One catalyst chemist has indicated that lanthanum improves methane conversion. While lanthanum has no oxygen storage capability, it can be used in place of cerium (since oxygen storage is not necessarily required) as a catalyst stabilizer. Thus, a natural gas catalyst system could be envisioned that would not use the A/F perturbations currently used for gasoline systems, and that would contain less oxygen storage material than gasoline systems. Such a system would probably not be able to use the oxygen storage measurement for OBD, since the perturbations needed for the oxygen sensor switching would be smaller and there would be little, if any, oxygen storage.

4. Dedicated LPG

In 1995 and 1996 there were no light-duty dedicated LPG vehicles offered by the automobile manufacturers. Ford has offered dedicated LPG medium-duty trucks (F600's and F700's) for a number of years. Chrysler is developing an LPG vehicle in Canada, with plans to offer it for sale in Canada in late 1996.

Even though there are no light-duty dedicated LPG vehicles offered for sale by the manufacturers, dedicated LPG vehicles are by far the most common alternate fuel vehicle in service today. In 1995 the Energy Information Administration estimated that there were
INPUT SENSORS TEED TO AFTERMARKET COMPUTER

FUEL INJECTOR OUTPUT "TRANSLATED" TO CNG METERING SIGNAL

FIGURE 13. TWO TYPES OF AFTERMARKET CNG FUEL CONTROL SCHEMES
(Adapted from Reference 30)
354,500 alternate fuel light-duty vehicles in-use, and that 223,200 of them, or 63 percent, were LPG fueled. All on-highway LPG-fueled vehicles have been converted to LPG from gasoline after the sale of the vehicle. Off-highway vehicles can sometimes be supplied with LPG fuel systems from the chassis manufacturer. An NREL study identified 32 companies that supply conversion kits for CNG and/or LPG. The Energy Information Agency estimates that there are 653 propane companies in the vehicle conversion business in the U.S. Some fleets even do their own conversions.

a. Fuel System

With so many conversion systems available, it not possible to cover all the configurations available. LPG conversion fuel systems are available in both open-loop and closed-loop configurations. A schematic of a closed-loop system manufactured by IMPCO (one of the largest manufacturers of LPG and CNG conversion systems) is shown in Figure 14 as an example of the hardware components used. This system, designated as an ADP system by IMPCO, is essentially a feedback carburetion system. The converter is the heart of the system. This device "converts" the LPG, which is a liquid entering the converter, to gas, and meters the gas flow to the air/fuel mixer.

It has been reported in the press that the Chrysler LPG van, being designed and built in Canada for the Canadian market, uses a multi-point liquid propane injection system. Liquid injection is expected to offer an advantage in more accurate fuel metering and in cold starting. The details of this system are not known at this time.

b. Control System

As noted above, current LPG vehicles are supplied by conversion companies. The vehicle manufacturers will not share the fuel control structure or computer program code with these conversion companies. Therefore, the fuel controls used in LPG vehicles are aftermarket controls. IMPCO has designed and built their own fuel controls. There are several other companies, for example DAI, which make fuel controls for propane conversion companies.

The Canadian Chrysler LPG van, being a liquid fuel system, can use a modified version of the standard gasoline fuel control. This system would obviously be a closed-loop control system, but just what additional inputs would be needed for this control, if any, are not known at this time.

c. Catalyst System

Even though all current dedicated LPG light-duty vehicles are aftermarket conversions, the catalyst is not necessarily the same as the OEM system. Recent conversion work done for the Clean Fleet Program LPG conversions used both stock gasoline catalysts and catalysts specially formulated for LPG.

A gaseous fuel study was recently conducted at SwRI for ARCO Products Company, and published in Reference 36. This study showed that on a stock vehicle with an IMPCO ADP kit installed, and with the same OEM catalyst, THC and NMOG FTP emissions, when run on 100 percent propane, were both lower than with Phase 2 gasoline. Thus, it appears that current OEM catalysts should suffice for LPG vehicles.
FIGURE 14. IMPCO CLOSED-LOOP LPG FUEL AND CONTROL SYSTEM
(Source: NREL Clean Fleet Final Report: Vol. 2, Project Design and Implementation)
The Chrysler LPG vehicles being developed in Canada will undoubtedly have catalysts designed specifically for an LPG vehicle. It is expected, however, that these catalysts would not be greatly different from current gasoline catalysts.

5. Bi-fuel Vehicles

The scarcity of refueling locations for gaseous fuels has resulted in vehicles that can run on either gasoline or a gaseous fuel, but only on one fuel at a time. The gaseous fuel can be either CNG or LPG. There are separate fuel tanks, engine fuel delivery systems, and controls for the gasoline and the gaseous fuel. Thus, the vehicle has two (or more) fuel tanks, two fuel delivery systems, and generally two separate fuel controls.

Currently, Ford is the only OEM to offer bi-fuel vehicles, but the gaseous fuel system for the vehicle is not Ford designed or factory installed. Ford uses what it calls its Qualified Vehicle Modifier (QVM) program to select gaseous fuel system manufacturers with whom to work to provide a bi-fuel vehicle. Bi-fuel vehicles can also be supplied by conversion companies. If demand were sufficient in the future, it could be expected that vehicle manufacturers would offer completely OEM designed and built bi-fuel vehicles.

a. Fuel System

The fuel systems for current bi-fuel vehicles are similar to the aftermarket dedicated systems for CNG and LPG, except that they must co-exist with the gasoline fuel system. This means that the gaseous fuel system will probably be a throttlebody induction system, since there is rarely room for two sets of injectors in the intake manifolds. It is reported in the press that the IMPCO LPG bi-fuel system used under the Ford QVM program is based on the ADP system shown in Figure 14.

b. Control System

Again, since bi-fuel vehicles are all conversions, the fuel control systems for CNG and LPG bi-fuel vehicles are similar to those used in the dedicated CNG and LPG vehicles discussed above. Since the gaseous fuel controls must co-exist with the OEM gasoline electronic control system, engine control for a bi-fuel vehicle is somewhat more complicated than for a dedicated CNG or LPG vehicle. Using a translator type system as described above would be one way to keep as much of the gasoline OEM fuel control as possible. The translator control could be switched on when the fuel was switched to the gaseous fuel.

c. Catalyst System

Since a bi-fuel vehicle can be operated on gasoline and either CNG or LPG, the catalyst system must be efficient for exhaust from either the gasoline or gaseous fuel. As discussed above, a gasoline catalyst will probably suffice for a bi-fuel vehicle using LPG. For CNG, a catalyst formulated specifically for natural gas would definitely provide better emission control when using CNG. One solution for a CNG bi-fuel vehicle would be to have a two-brick catalytic converter, one brick formulated for gasoline and one for CNG, with each brick slightly oversized compared to a single-fuel, two-brick system. It is doubtful that current bi-fuel conversions to CNG have included catalyst replacement. In the future, however, when these vehicles are required to meet California LEV and ULEV standards, more consideration will need to be given to the catalyst system.
V. OBD CAPABILITY ON ALTERNATE FUELED VEHICLES

Section III discussed the technology for the nine required Federal OBD areas. Section IV discussed the technology used by different types of alternate fuel light duty vehicles. From an examination of the information in Sections III and IV, five of the OBD areas were found not to be affected by the type of fuel used. Those areas not affected are:

- Engine misfire
- Oxygen sensor monitor
- EGR monitor
- Secondary air
- Continuity of components monitored.

This report will not discuss these five areas. There are, however, four OBD areas that are affected by the type of fuel. These areas are:

- Catalyst monitor
- Fuel system trim
- Idle air control
- Evaporative system monitor.

In the paragraphs below, the four OBD areas that are affected by the use of alternate fuels are discussed by individual OBD area. This section will be concluded with a discussion on the special problems of gaseous fuel conversion vehicles.

A. Catalyst Monitor

Currently all manufacturers use the dual oxygen sensor method for catalyst monitoring. This system is the subject of much discussion in the technical literature. The application of the dual oxygen sensor method to alternate fuel vehicles is discussed below.

1. All Alternate Fuel Vehicles

While a relationship can be established between oxygen storage and HC efficiency for current production catalysts at catalyst efficiencies below 90 percent, this relationship appears to break down at the high efficiencies (above 90 percent) which are required to meet future CARB and EPA standards. CARB, however, believes that the dual oxygen sensor technique will work for LEV technologies, and in a telephone conversation, stated that one manufacturer has approached them with plans to use the dual oxygen sensor method for ULEV. Thus, a more detailed look at the dual oxygen sensor method is in order.

The question regarding the use of the dual oxygen sensor method is this: is there a relationship between oxygen storage and HC efficiency? By broadening the "window" of optimum efficiency, oxygen storage certainly contributes to HC control. But, oxygen storage appears to be related to the amount of cerium in current technology catalysts, and the continual switching of the fuel/air ratio across the stoichiometric point which is caused
by the discrete, either rich-or-lean signal from the oxygen sensor. There is no question that
high HC efficiencies can be achieved without oxygen storage. Early three-way catalysts did
not have cerium in the washcoat and exhibited little oxygen storage, yet many of these
catalysts had high steady state efficiencies. Several SAE papers from the early nineties
present data indicating the difficulty in defining a relationship between oxygen storage and
catalyst hydrocarbon conversion efficiency at the high HC efficiencies (>90%). OBD
techniques and catalyst systems are currently being developed to overcome these difficulties.

While there are still questions about the relationship of oxygen storage to
catalyst efficiency, there is no question that efficiency can be related to oxygen depletion
across the catalyst. It is important, therefore, to realize that none of the dual oxygen sensor
techniques measures oxygen depletion across the catalyst, indeed the switching type oxygen
sensors cannot measure oxygen depletion. One SAE paper, Reference 8, discusses the reason
why these oxygen sensors do not measure oxygen depletion, and proposes some methods to
develop oxygen sensors that can measure oxygen depletion.

Another approach that has been discussed in several SAE papers, but not used
on production vehicles, is to measure the exothermic reaction (i.e., the temperature rise) of
the catalyst, which is proportional to its efficiency. A third approach is to directly measure
the hydrocarbon level in the exhaust using some currently non-existent, low cost, hydrocarbon
sensor. There is little information in the literature on hydrocarbon sensors, but there is a
great deal of interest in such devices. SwRI has been approached by several companies
interested in exploring the possibility of developing an exhaust hydrocarbon sensor. Exhaust
hydrocarbon sensing is the subject of some CRADA work at Oakridge National Lab. Practical
hydrocarbon sensors for production vehicles are estimated by SwRI to be at least five years
away, and very possibly longer. The conclusion, then, is that OBD catalyst monitoring is
apparently still a problem for all vehicles, including those using an alternate fuel.

2. Special Considerations for Dedicated CNG Vehicles

While the discussion in this section is applicable to all alternate fuel vehicles,
the use of dual oxygen sensors may be more difficult for dedicated natural gas vehicles that
use a catalyst specifically designed for natural gas exhaust. This difficulty could arise as a
result of the natural gas catalyst washcoat composition, which could be different from that
of a gasoline catalyst washcoat.

Emissions from CNG vehicles do not benefit from the relatively wide rich-lean
swing across the stoichiometric point that is currently used on gasoline vehicles. In fact,
emissions are lowest on CNG vehicles when the air/fuel ratio is tightly controlled.\(^{29,32,34}\) New fuel control algorithms are permitting tighter control of the air/fuel ratio. If the air/fuel
ratio is held tighter, there is no need for the oxygen storage capabilities of cerium, which is
also used as a high temperature stabilizer in the washcoat. Both lanthanum and barium,
which have no oxygen storage capability, are more recognized as stabilizers than cerium, and
could be used in natural gas catalysts.\(^{6}\)

It has also been found that catalysts using only palladium as the active metal
provide better HC control for CNG vehicles.\(^{29,32}\) Thus a CNG vehicle, designed to meet
ULEV and stricter standards, could easily be envisioned to have very tight air/fuel control
around stoichiometric, and use a Pd-only catalyst with lanthanum as a stabilizer. The
exhaust of such a vehicle would not exhibit appreciable swings in air/fuel ratio, and the
catalyst would have little oxygen storage even at low mileage. Thus, the current dual oxygen sensor technique would not be usable for catalyst efficiency monitoring for this possible CNG vehicle.

B. Fuel System

The fuel system is, of course, at the heart of the difference between alternate fuel vehicles and the current production gasoline fuel vehicles. This section discusses how fuel system differences affect the use of current OBD technology for monitoring fuel system trim.

1. Methanol and Ethanol (Dedicated or Flexible Fuel Vehicles)

The only functional difference (there are some materials differences) between a gasoline fuel system and an alcohol fuel system is found in flexible fuel vehicles (FFVs). Since any possible combination of gasoline and alcohol can exist in the FFV fuel tank at any time, an FFV fuel system uses a fuel composition sensor to determine proper engine fueling. To meet OBD regulations, this fuel composition sensor must be checked to ensure that it is functioning properly.

No information was found in the literature on how fuel composition sensors might meet OBD requirements, or even if the failure of the sensor would cause the EPA emission limits to be exceeded. However, SAE Recommended Practices for OBD list the fuel composition sensor. SAE J1930, which defines the preferred terms for use with OBD, lists the preferred term for fuel composition sensor as “flexible fuel sensor.” SAE J2012, Diagnostic Trouble Code Definitions, has codes for fuel composition sensor circuit malfunction (P0176), circuit range/performance (P0177), circuit low input (P0178), and circuit high input (P0179). Thus, monitoring of the fuel composition sensor has certainly been planned.

The sensors can, of course, be checked for out-of-range voltage. If, however, they are to be checked for proper functioning (i.e. correct percent of alcohol signal), then another method to infer the fuel composition must be available. A Mitsubishi prototype FFV, described in Reference 25, used a comparison of the oxygen sensor output to a reference output as a second method of determining the fuel composition. Presumably, at some operating condition, the two values could be compared to determine if the fuel composition sensor was operating correctly. With all the sensor outputs now available to the controller, there should be enough information, if used with the correct algorithm, to determine if the fuel composition sensor is providing the correct fuel composition. The task is one of finding the right algorithm.

2. OEM Produced Dedicated CNG or LPG Vehicles

Dedicated CNG or LPG vehicles produced by an automobile manufacturer will probably have multipoint fuel injection systems. Examination of a CNG fuel system from an OEM shows that the system includes a pressure and temperature sensor, so that the density of the fuel is known. Once the density of the gaseous fuel is known, the fuel system trim can be monitored by the same algorithms that are used for gasoline engines. So it is expected that dedicated LPG and CNG vehicles manufactured by OEM’s will be able to meet OBD requirements.
3. Conversions to Dedicated or Bi-Fuel CNG and LPG Vehicles

As discussed in Section IV, there currently are no light duty, dedicated LPG vehicles manufactured by OEM's in the United States. Thus, all dedicated LPG vehicles are conversions. In addition, most of the CNG vehicles in service are conversions.

Field conversions of vehicles from gasoline to dedicated CNG or LPG may either be multipoint injection or throttle body systems. The throttle body system can use either an injector of some sort, or a gas induction valve. Thus, these systems may be similar to the OEM systems in design, or they may be quite different. For fuel systems that are similar to OEM systems, the dedicated OEM discussion above applies, except that the fuel control technology available to the OEM may not be available to a conversion company. Systems that are different in design philosophy from OEM systems will likely be simpler systems. These systems may not have pressure or temperature sensors in the fuel line, and may even be open loop systems.

The fuel control on CNG and LPG conversion systems will probably be far less sophisticated than the OEM fuel control, may lack the capability for processing signals from multiple sensors, and may lack complex algorithms. Thus, a conversion CNG or LPG fuel system may have deficiencies, both in the fuel system hardware and the fuel control electronics, that prevents it from meeting all OBD fuel trim requirements.

Bi-fuel vehicles have gasoline fuel systems that were developed by an automobile manufacturer, and a gaseous (CNG or LPG) fuel system developed and installed by a different company. The vehicle, as produced with the gasoline fuel system, will presumably meet the OBD requirements applicable to that vehicle. It is the responsibility of the installer of the gaseous fuel system to ensure that this system meets the applicable OBD requirements, and does not interfere with the gasoline OBD system. The discussion above on dedicated CNG and LPG conversions also applies to bi-fuel vehicles in this regard.

For bi-fuel vehicles, the MIL must not come on when the fuel is shifted from gasoline to the gaseous fuel, as it might if the sensors indicated that the gasoline fuel system was not operating. Given the present architecture of the OEM engine controllers, close cooperation with the vehicle manufacturer is currently needed to meet this requirement. At this time vehicle manufacturers are reluctant to provide this cooperation.

An engineering source at IMPCO refers to not lighting the MIL while using LPG as being "OBD compatible." The IMPCO control system used in the Ford QVM pickup truck is OBD compatible. This does not mean the IMPCO LPG system complies with all the Federal OBD or California OBD-II fuel system monitoring requirements. “Compatible” means only that while running on LPG, the system will not give a false MIL lighting signal because the gasoline system is not operating, and that it will not interfere with the functioning of the OBD systems when the vehicle is running on gasoline.

C. Idle Air Control

Most electronic fuel injection systems have a solenoid type valve (often referred to as the idle air control (IAC) valve, to allow some air to bypass the throttle during idle and other closed throttle operation. The IAC valve has several functions, including control of air flow during starting and idle for different engine starting temperatures, and providing additional air during decels to prevent stalling and exhaust hydrocarbon spikes. The operation of the
IAC valve is controlled by the engine electronic control system. Where installation of an alternate fuel system is done by other than the OEM, the aftermarket alternate fuel system may or may not use the OEM IAC calibration (it could also disable the OEM IAC), and may or may not provide the equivalent of an IAC. Thus, the usual OBD monitoring of the IAC valve may not correctly indicate the status of idle air control. The likelihood of such problems differs according to alternate fuel and entity responsible for final fuel system design and assembly, as indicated in the following subsections.

1. **Methanol and Ethanol (Dedicated or Flexible Fuel Vehicles)**

Since dedicated alcohol vehicles or FFVs's use functionally the same fuel system and fuel controls as current gasoline vehicles, the OBD idle air control monitoring can be the same as for gasoline vehicles. Thus, OBD monitoring of idle air control for alcohol vehicles is not a special problem for FFVs.

2. **OEM Produced Dedicated CNG or LPG Vehicles**

OEM produced dedicated CNG vehicles, such as the Ford Crown Victoria and Chrysler minivan, have OEM current technology multipoint fuel injection systems. These systems, too, can utilize the gasoline idle air control systems. Thus, OBD monitoring of idle air control systems for OEM produced dedicated CNG vehicles is no more of a problem than it is for gasoline vehicles.

3. **Conversions to Dedicated or Bi-Fuel CNG and LPG Vehicles**

SwRI has installed several gaseous conversion systems over the past several years. One older system required that the IAC valve be blocked off in order for the engine to start acceptably. Newer systems do not require this practice. At least one current conversion system provides its own idle air control. Future conversions could provide idle air control OBD in the same manner as current gasoline vehicles. The solution would, once again, require interfacing with the OEM controller.

D. **Evaporative System Monitor**

Since current evaporative system OBD monitoring hardware and procedures were developed specifically for gasoline systems, the OBD hardware and procedures needed for alternate fuel vehicles may be different.

1. **Methanol and Ethanol (Dedicated or Flexible Fuel Vehicles)**

Alcohol-gasoline blends such as M85 and E85 may have higher RVP than gasoline alone, and in addition, blends behave as more volatile fuels than gasolines of equal RVP (that is, with an increase in vapor-to-liquid ratio, the vapor pressure of blends is higher than the vapor pressure of gasoline). The more volatile behavior of M85 and E85 can be compensated for in the design of the evaporative control system. For example, on Honda's prototype M85 vehicle, a larger evaporative canister was used, and larger vapor lines together with a fuel tank having larger volume-to-surface ratio were installed to reduce fuel tank pressure. Thus, while the M85 and E85 fuel characteristics are different from gasoline, there appears to be no problem with using gasoline OBD methodologies for alcohol blends.
2. Dedicated CNG and LPG Vehicles

For this topic, the CNG and LPG vehicles will be discussed together. Since they both have closed fuel systems, they have no evaporative emission control system. With no evaporative emission control system, this OBD requirement does not apply to these vehicles.

3. Bi-Fuel Vehicles

Bi-fuel vehicles have a complete gasoline evaporative emission control system that should be fully OBD compliant when running on gasoline. When operating on the gaseous fuel (either CNG or LPG), there could be problems. The gaseous fuel system itself will not present additional OBD requirements, since, as discussed above, these are closed systems. The problem is with the OEM gasoline evaporative system.

All bi-fuel vehicles are essentially conversions. The conversion company must decide what to do with the gasoline evaporative system during the use of gaseous fuel. Even while the vehicle is operating on gaseous fuel, the gasoline fuel tank is producing vapors. If the evaporative system is completely closed, unsafe pressures could build up within the tank. If the vapor is allowed to vent into the canister, but the canister is never purged to the engine, then, over long periods of gaseous fuel use, the canister could saturate. Thus, it would seem logical to have the gasoline evaporative control system functional, even when operating on gaseous fuel.

The problem with keeping the evaporative system functional during gaseous fuel operation is the same problem bi-fuel vehicles have with all OBD requirements: how to interface with the OEM engine controller. This interface will depend on the design of the gaseous fuel control. If the controller is a stand-alone system, it must provide the necessary commands and data processing for the evaporative system; and in addition, not permit the MIL to be illuminated by the OEM controller because the evaporative system no longer responds to the OEM control. If the control interface is intended to use the part of the OEM controller that controls the evaporative system, then, for current OEM controllers, close cooperation with the OEM is required.

E. Special Considerations for Gaseous Fuel Conversion Vehicles

The problem of aftermarket conversions interfacing with OEM engine controls has been highlighted throughout the discussions in this report. Except for the need to measure pressure and temperature in the gaseous fuel supply at the engine, and the possible need for a different catalyst monitor for some natural gas catalysts, gasoline vehicle OBD technology can be used to meet OBD requirements for gaseous fuel vehicles. To be fully compliant with OBD requirements, conversion companies need either stand-alone engine controls as sophisticated as the OEM controller, or access to the computer codes of the OEM controller. The current level of sales of gaseous fuel light duty vehicles does not generate enough capital, either as profit or venture capital, for conversion companies to fund development of a stand-alone engine controller that will provide all the functions of the OEM engine controller.

For their part, OEM's regard the engine controller hardware and algorithms as proprietary, and will not generally permit access to their controllers by aftermarket companies. This situation is changing somewhat with Ford's QVM program, but the QVM program is the still exception rather than the rule.
VI. OBD DEVELOPMENT NEEDED FOR ALTERNATE FUELS

From the discussions in Section V, it can be seen that there are three areas where the application of current OBD technology is insufficient for alternate fuel vehicles, and where additional development is needed. These three areas are: (1) catalyst monitoring, (2) alcohol fuel composition sensor monitoring for FFV's, and (3) conversion vehicles in general. The first two are technical needs which should yield to further research and development, though not necessarily in the time frame of current EPA and CARB regulations. The third area of need is as much an economic as technological. These three areas are discussed in further detail below.

A. Catalyst Monitor

As discussed in Sections III and V, the needed developments in catalyst efficiency monitoring are generic to all fuels, and so are not a special need of alternate fuel vehicles, with the possible exception of natural gas vehicles. Although development work is still needed, the dual oxygen sensor approach will probably be sufficient for currently planned LEV and ULEV systems. The other approaches to catalyst monitoring that are being investigated are still very much in the development stage.

The alternate approach that is most developed is the use of durable temperature sensors and algorithms to determine the catalyst exotherm, which can be related to catalyst efficiency. Two other approaches involve development of sensors for exhaust gases. One approach is to develop a true oxygen sensor that could be used to measure oxygen depletion across the catalyst. The second sensor approach is to use a hydrocarbon sensor to directly measure catalyst hydrocarbon efficiency. Neither of these sensors has been developed, and from the few remarks found in the literature, their development is not imminent. Thus, there is a need for additional development of catalyst efficiency monitoring systems for all vehicles, including alternate fuel vehicles.

This need could be greater for some CNG vehicles. As indicated in Sections IV and V, it is possible that future CNG vehicles will have tighter air/fuel ratio control and catalysts with inherently less oxygen storage. These two features would make it even more difficult to use the current dual oxygen sensor method to infer catalyst hydrocarbon conversion efficiency on natural gas vehicles. Thus, it would appear that if a CNG vehicle were developed in the near future with the characteristics postulated here, it would have an even greater need for new technology for catalyst efficiency monitoring.

B. Alcohol Fuel Composition Monitor

Fuel composition monitors are only installed on FFV's, so OBD monitoring of the sensor applies only to these vehicles. There is no discussion in the literature of how this sensor could be monitored for correct performance. Combustion parameters, however, do change with fuel composition. It is expected, therefore, that a technique to monitor the fuel composition sensor could be found with moderate effort. Thus, this needed development is not expected to be a long term problem for OBD compliance of FFV's.
C. **Conversion Vehicles**

There are two general tasks facing the conversion industry: (1) providing OBD for the equipment they install, and (2) ensuring that disabling OEM systems will not cause the MIL to be illuminated. Most of the technical needs of the conversion industry center around either developing their own sophisticated controller or having some access to the OEM controller. The solution to the needs associated with gaseous fuel conversion vehicles meeting the OBD requirements are as much economic as technical in nature, however. Conversion companies, because of the limited capital that can be generated by the relatively small volume of vehicles sold, may find it almost impossible to develop independent systems to meet all of the OBD requirements. The CNG and LPG industry press (magazines, newsletters, and the like) identify OBD-II as the biggest problem facing vehicle conversion companies.\(^{39}\)

The problem is simply that not enough light-duty gaseous fuel vehicles are being sold. An automotive OEM was quoted in an propane industry magazine as saying that a potential market of at least 20,000 vehicles per year is necessary to justify any vehicle model.\(^{40}\) While alternate fuel vehicle sales data are difficult to obtain and assemble, it would appear that even with Federal mandates, the **total sales of gaseous fuel light duty vehicles in 1996** was probably less than 20,000 for all suppliers.\(^{35}\) Chrysler, in announcing it would no longer supply natural gas vehicles, said it sold only about 700 of these vehicles in 1996.\(^{27}\) IMPCO, in discussing its participation in the Ford QVM program, indicated it hoped for sales of about 2000 vehicles.\(^{41}\) A June 1994 Energy Information Administration (EIA) report estimated total sales of light-duty LPG vehicles in 1994 to be about 9000.\(^{42}\)

If the gaseous fuel vehicle market becomes large enough for the OEM’s to start producing large volumes of either dedicated or bi-fuel vehicles, then the aftermarket conversion companies will disappear from the on-road market, along with the special needs of these companies. However, as long the majority of gaseous fuel systems in service are from conversion companies, it is likely the need for OBD systems for fuel system trim and bi-fuel vehicle evaporative emission systems will continue.
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