Technical Opportunities and Challenges to Reduce Gasoline Consumption from the In-Use LDV Fleet through Retrofit and Alternative Fuel Conversion Technologies

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1. Background / Introduction

The National Highway Traffic Safety Administration (NHTSA) recently began implementing new fuel economy standards for new light-duty vehicles (LDVs) through model year (MY) 2016, in conjunction with the U.S. Environmental Protection Agency's (EPA) greenhouse gas (GHG) standards covering the same vehicle class and model years. The two agencies have proposed a second round of even stricter standards through MY 2025. Both sets of standards were jointly developed by NHTSA, EPA, and the California Air Resources Board (CARB). In August 2012, the Obama administration issued the final version of these new rules, which nearly double the average fuel economy of new LDVs by 2025. These newest fuel economy standards will substantially reduce new vehicle fuel consumption and GHG emissions in the United States.

However, the actual quantity of petroleum fuel reductions that can be achieved in the prescribed timeframe will depend in part on how fast newer technologies and/or alternative fuels can be introduced into the existing ("legacy") LDV fleet. In 2011, the U.S. LDV fleet consisted of approximately 235 million in-use LDVs (cars and light trucks). In the same year, annual new vehicle sales included approximately 12.6 million LDVs, or about 5 percent of the in-use fleet.[1,2] Based solely on the rate at which new vehicles are deployed, it will take many years to incorporate newer, more-fuel-efficient and alternative-fuel LDVs into the existing fleet.[3]

Greater petroleum displacement and GHG reductions can be realized if large numbers of vehicles in the legacy LDV fleet can be retrofitted to 1) exhibit better fuel efficiency and therefore reduce gasoline consumption, or 2) enable operation on low-carbon alternative fuels. Conversion of legacy fleets to alternative fuels has been successfully implemented throughout the world, especially for natural gas and propane fuels. A key issue with either kind of vehicle retrofit / conversion in the U.S. is how these technologies will affect the very sophisticated emissions control systems and on-board diagnostics of today's gasoline LDVs. Both the EPA and CARB have regulations in place to prevent tampering with vehicle emission control systems. These include provisions to insure that vehicle emissions are not degraded by the addition of retrofits or aftermarket parts and systems.

The objective of this assessment is to assess the feasibility of, opportunities for, and barriers to retrofitting or converting existing late-model LDVs in the U.S. to improve fuel economy, and/or to use ethanol or methanol fuels. Feasibility parameters that have been considered include technical, institutional, regulatory and economic factors. Key overarching issues include the following:

1. Will sale or installation of the aftermarket system violate federal and/or state anti-tampering provisions under the Clean Air Act (or other regulations)?

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[1] Massachusetts Institute of Technology, "On the Road in 2035, Reducing Transportation Petroleum Consumption and GHG Emissions," Laboratory for Energy and the Environment, July 2008, accessed online at: http://web.mit.edu/sloan-auto-lab/research/beforeh2/otr2035/On%20the%20Road%20in%202035_MIT_July%202008.pdf.

[2] U.S. Department of Transportation, Research and Innovative Technology Administration, Bureau of Transportation Statistics, "National Transportation Statistics: Table 1-11: Number of U.S. Aircraft, Vehicles, Vessels, and Other Conveyances," accessed online at: http://www.bts.gov/publications/national_transportation_statistics/excel/table_01_11.xls.

[3] Some LDV-use sectors (e.g., taxicabs and delivery vehicles) have much higher annual vehicle miles traveled (VMT) than others. Thus, the real metric of importance for displacing petroleum in the LDV legacy fleet will be the rate it takes for higher efficiency and alternative fuel vehicles to increasingly contribute to total VMT.

2. What are the aftermarket system's effects on the original vehicle's warranty, including emissions performance clauses?

3. Will the aftermarket system negatively impact the performance, safety or utility of the original vehicle?

2. Assessment of Aftermarket Retrofits to Improve LDV Fuel Economy

This section discusses the regulatory and technical feasibility of retrofitting in-use LDVs with aftermarket hardware and/or software systems that can cost-effectively improve their fuel economy.

2.1 U.S. EPA / Federal Oversight and Testing for Retrofit Devices

EPA defines a "retrofit device" as:

> "*Any component that is designed to be installed in or on an automobile (as an addition to, a replacement for, or through alteration or modification of any original component, equipment, or other device) that the manufacturer states will provide higher fuel economy and/or lower emissions. The term also includes fuel additives for use in an automobile.*"[4]

Technically, EPA's approval is not required for a retrofit device to be legally sold in the United States.[5] Nonetheless, EPA has shown keen interest in such devices for their potential effects on emissions and fuel economy of in-use vehicles. Aftermarket retrofit devices present a conundrum for EPA. On the one hand, devices may exist that can significantly improve fuel economy and/or reduce emissions when retrofitted on LDVs within America's large in-use fleet. The dilemma for EPA is that installation of such devices can potentially constitute "tampering" with the vehicle's stock emissions control system, which is illegal under Section 203(a)(3) of the Clean Air Act (Act). EPA's policy has always been that any alteration from an original configuration of a certified vehicle or engine may constitute illegal tampering with the vehicle's emissions control system. EPA's ultimate goal is to ensure that emissions levels of certified in-use vehicles will not be increased through the addition of retrofit devices.

In addition to these concerns about potential tampering and increasing emissions levels, EPA expresses other concerns about aftermarket systems designed to modify in-use vehicles. All of these are summarized in the following warning to vehicle owners found on EPA's website[6]:

> *"Any additions or changes to your car's engine, emission system, fuel system, or exhaust system have the potential to cause one or more of the following problems:*
>
> - *Increased emissions*
> - *Reduced fuel economy*
> - *Harm to your vehicle*

[4] EPA, "Evaluation Program for Aftermarket Products That Are Intended to Improve Fuel Economy or Reduce Emissions," available at http://www.epa.gov/otaq/consumer/420f11013.pdf

[5] Personal communication from EPA staff to TIAX, June 6, 2012.

[6] EPA, "Devices and Additives to Improve Fuel Economy and Reduce Pollution – Do They Really Work?", accessed online at http://www.epa.gov/otaq/consumer/420f11036.htm.

- *Void the manufacturer warranty*
- *Create safety or environmental hazards*
- *Violate the federal prohibition against tampering"*

2.1.1 EPA's Anti-Tampering Enforcement Program

The general purpose and contours of EPA's anti-tampering enforcement program regarding aftermarket vehicle retrofit and conversion systems have been clear and unwavering for several decades. The prohibition on tampering is contained in section 203(a)(3)(b) of the Clean Air Act itself, which prohibits changing a vehicle so as to negatively impact compliance with emission standards over the life of the vehicle:

> *"The following acts and the causing thereof are prohibited. . . to manufacture or sell, or offer to sell, or install, any part or component intended for use with, or as part of, any motor vehicle or motor vehicle engine, where a principal effect of the part or component is to bypass, defeat, or render inoperative any device or element of design installed on or in a motor vehicle or motor vehicle engine in compliance with regulations under this title, and where the person knows or should know that such part or component is being offered for sale or installed for such use or put to such use ...."*[7]

EPA, in turn, has developed anti-tampering policies enforcing this statutory prohibition, with periodic updates clarifying their scope and practical application. As agency policies, these guidelines and interpretations do not have the same legal force as regulations, and so are not as binding on the agency. EPA must, however, generally provide a reasoned explanation for any deviations from the policies in its enforcement actions against manufacturers, sellers, and installers.

In 1974, EPA's Office of Enforcement and General Counsel issued Mobile Source Enforcement Memorandum 1A (Memo 1A) to provide guidance about the definition of and enforcement against tampering, specifically with respect to maintenance and the use of aftermarket parts. Memo 1A provides, in part, that the use of an aftermarket part, alteration or add-on part will not constitute tampering if the dealer has a "reasonable basis" to believe that such acts will not adversely affect emissions performance. It also provides specific procedures or options by which the dealer would have a "reasonable basis" to make such conclusions.

In 1997, EPA issued an addendum to Memo 1A that clarified and revised its anti-tampering enforcement policy. This noted that emissions testing can be conducted as one means to form a "reasonable basis."[8] According to the addendum, Memorandum 1A "basically" states that:

> *"EPA will not consider any modification to a certified emissions control configuration to be a violation of the tampering prohibition if there is a reasonable basis for knowing that emissions are not adversely affected. In many cases, durability aging and emissions testing according to the FTP would be necessary to make this determination. There are two different methods for establishing a reasonable basis for knowing that emissions are not*

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[7] 42 U.S.C. § 7522(a)(3)(B).

[8] EPA, "Addendum to Mobile Source Enforcement Memorandum 1A (Tampering Enforcement Policy)," September 4, 1997, available at: http://www.epa.gov/compliance/resources/policies/civil/caa/mobile/admem1a.pdf.

adversely affected by the installation of a retrofit device: 1) the installer knows of, or the manufacturer of the device represents in writing, that FTP emission tests have been performed as prescribed in 40 CFR 86 showing that the device does not cause similar vehicles to fail to meet applicable emission standards for their useful life; or 2) a federal, state or local environmental control agency expressly represents that a reasonable basis exists. Such an agency determination is limited to the geographic area over which that agency has jurisdiction. Some states, such as California, have additional requirements."

In 2000, EPA provided the following clarification about anti-tampering considerations specific to onboard diagnostic systems (that had already taken effect years ago):

EPA cautions applicants that the installation of an aftermarket retrofit device, or use of a fuel additive. . . . raises the issue of tampering liability and the potential for civil fines of up to $25,000. In the past, one approach for a device or additive manufacturer to address the tampering issue was to demonstrate by durability, aging, and FTP tests that the device did not increase vehicle emissions over its useful life. However, beginning with 1994 models, vehicle manufacturers must provide an onboard emission diagnostic capability for their vehicles. As a consequence, applicants must ensure that, besides not adversely affecting vehicle emissions, their device or additive must not render inoperative, degrade, or defeat the operation of vehicle onboard diagnostic systems.[9]

2.1.2 Pollutant Trade-offs and Tampering

The above system generally disallows trade-offs between pollutants when determining whether a retrofit device or conversion system runs afoul of the Act's tampering prohibition. This negative stance on pollutant trade-offs is consistent with the Act's treatment of new vehicles, for which the statute takes an individual approach to pollutants and disallows degradation in emissions performance.[10] Furthermore, disallowing pollutant trade-offs is critical to the success of State Implementation Plans for attaining the National Ambient Air Quality Standards – allowing an increase in one pollutant from existing vehicles could throw off the careful balance set in developing the state plans.

Looking at a specific subset of potential pollutant trade-offs that may arise in the retrofit or conversion context, Memorandum 1A can be read as allowing small or de minimis increases in one pollutant where a device achieves significant decreases in another pollutant, as long as the proponent of the device can still demonstrate compliance with the applicable emission standard for the first pollutant over the life of the vehicle.[11] In other words, where a vehicle had a

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[9] EPA, "EPA Motor Vehicle Aftermarket Retrofit Device Evaluation Program," EPA publication 420-B-00-003, May 2000, PDF accessed online at: http://www.epa.gov/oms/consumer/b00003.pdf.

[10] See 42 U.S.C. § 7521(a)(1), (b)(1)(A) and (B), and (g)(1) and (2) (individual pollutant focus); 7521(b)(1)(C),

[11] *See* Memorandum 1A at (b)(3)(a) ("the dealer knows of emissions tests which have been performed according to testing procedures prescribed in 40 CFR section 85 showing that the act does not cause similar vehicles or engines to fail to meet applicable emission standards for their useful lives.") California Vehicle Code Section 27156 sets a baseline of no emission increases, but also appears to allow for some de minimis increase in emissions if CARB issues a resolution finding that the vehicle will remain below the applicable standard(s). *See* Section 27156(c) (prohibiting devices that alter or modify the original performance of the pollution control device of system) and (h)(2) ("This section shall not apply to an alteration, modification, or modifying device, apparatus, or mechanism found by resolution of the State Air Resources Board to do either of the following… To result in emissions from the modified or altered vehicle that are at levels that comply with existing state or federal standards for that model-year of the vehicle being modified or converted.")

significant margin of compliance as a new vehicle, the retrofit device may be allowed to consume some of that margin without running afoul of the tampering prohibition.

However, as a practical matter, there are significant technical hurdles to passing emissions testing while increasing one pollutant in the interest of reducing another. Manufacturers of new vehicles build in margins of compliance to ensure that their vehicles will continue to meet applicable standards over their lifetime, and retrofit device proponents may not have access to all of the testing done to simulate wear, age, etc. which would be used to set that margin to ensure lifelong compliance. In addition, new vehicle manufacturers meet standards on a fleet-wide basis, such that any change in emissions of one pollutant from one vehicle may throw off the fleet's compliance. So while in theory one could increase emissions in a pollutant without risking a tampering enforcement action by EPA, in practice doing so will be quite difficult.

2.1.3 EPA's "511" Aftermarket Retrofit Device Evaluation Program

In addition to prohibiting and guarding against tampering, EPA has historically evaluated the efficacy of retrofit devices that claim to improve fuel economy and/or reduce exhaust emissions. To help meet both objectives, EPA established its Aftermarket Retrofit Device Evaluation Program, also known as the "511 Program." The 511 program was designed to "generate, analyze, and disseminate technical data on the effectiveness" of aftermarket devices and fuel additives. EPA describes it as follows:

> *"Through engineering and/or statistical analysis of data from vehicle tests, the evaluation program determines the effects on fuel economy, exhaust emissions, durability and drive-ability of the applicable vehicles due to the installation or use of the device. Data generated in an evaluation are public information and will be published in the Federal Register and elsewhere for use by the FTC and the public."*[12]

Notably, EPA does not approve, certify, endorse, or register any products that pass through this voluntary evaluation program. Similarly, EPA does not approve, certify, endorse, or register any independent laboratory or the test results from any independent laboratory. EPA notes that any claims to the contrary by device manufacturers and marketers are false.[13]

EPA states the following about the relationship between its anti-tampering enforcement program (codified in the updated Memorandum 1A) and its 511 program to test retrofit devices:

> *"If the results of EPA emission testing of a retrofit device show that any of the regulated emissions increase (even though other regulated emissions may have decreased), EPA will publish a Federal Register Notice (Notice) explaining the legal implications of those findings on persons engaged in the business of servicing, repairing, selling, leasing, or trading motor vehicles, fleet operators, new car dealers and individuals. The Notice will alert the regulated parties that the installation of such a device by them may be deemed to be a violation of section 203(a)(3) of the Act.*

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[12] EPA, "EPA Motor Vehicle Aftermarket Retrofit Device Evaluation Program," EPA publication 420-B-00-003, May 2000, PDF accessed online at: http://www.epa.gov/oms/consumer/b00003.pdf.

[13] EPA, "Evaluation Program for Aftermarket Products That Are Intended to Improve Fuel Economy or Reduce Emissions," available at http://www.epa.gov/otaq/consumer/420f11013.pdf.

EPA does not have a mandatory, formal program to evaluate and make determinations of compliance of aftermarket parts with Memorandum 1A. Although EPA has informally evaluated compliance information in the past, because of current budget cuts and resource constraints we are not routinely reviewing information showing compliance with Memorandum 1A. While compliance with Memorandum 1A is required, submission of the information to us is not required unless we request the information to verify compliance. We emphasize, however, that our lack of review of the information does not relieve any one from responsibility to comply with Memorandum 1A or liability for violations of section 203(a)(3) and Memorandum 1A." [14]

2.1.1.1 Procedures for Retrofit Device Testing Under EPA's 511 Program

Originally, the process to get a retrofit device evaluated under EPA's 511 Program was as follows:

1. A device evaluation can be initiated via request from: 1) EPA, 2) the applicant, or 3) the Federal Trade Commission. If the applicant requests the evaluation:

2. The applicant submits a form describing details about the technology and its intended use.

3. The applicant "self-funds" emissions testing on one or more vehicle(s) at an EPA-approved independent laboratory, using EPA's prescribed test procedures and protocols described in EPA's May 2000 publication (http://www.epa.gov/oms/consumer/b00003.pdf). The estimated cost for this testing depends on many variables (e.g., the nature of the retrofit device, numbers of test vehicles). According to EPA, the "minimum test plan" to evaluate fuel economy impact involves a fleet of two cars tested in triplicate. EPA's May 2000 brochure estimates a minimum cost of $27,000 for 511 testing at EPA's lab. In recent discussions with EPA staff, a more up-to-date estimate of about $40,000 per vehicle was offered (if tested at either EPA or an independent lab). However, worst case it can take multiple vehicles and a large test matrix to fully perform the necessary testing. Thus, 511-type emissions and fuel economy testing in 2012 to obtain a CARB EO could cost $80,000 to $100,000. (Additional discussion and details are provided in subsequent sections of this report.)

4. The independent lab's test data is submitted to, and evaluated by, appropriate EPA staff.

5. If the test data show a statistically significant improvement (at least 5%)[15] in fuel economy EPA conducts a second set of emissions / fuel economy testing at the National Vehicle and Fuel Emissions Laboratory (NVFEL) in Ann Arbor, Michigan.[16] (If "No", EPA posts results without further testing.)

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[14] EPA, "EPA Motor Vehicle Aftermarket Retrofit Device Evaluation Program," EPA publication 420-B-00-003, May 2000, PDF accessed online at: http://www.epa.gov/oms/consumer/b00003.pdf..

[15] "According to EPA, "If a minimum five percent difference in average fuel economy is shown, one may usually conclude with reasonable confidence that a real improvement exists." However, EPA's analysis for potential fuel economy effects is based on "actual test results and test variability, not these guidelines."

[16] Presumably, device manufacturers would not submit their product for further testing if the independent lab testing showed no significant fuel economy benefit and/or an increase in the test vehicle's emissions. This could prompt EPA compliance testing.

6. EPA posts results of the device's NVFEL emissions testing (whether positive or negative) on its website and in the Federal Register.

2.1.1.2 Devices Tested Under EPA's 511 Program and Summary of Results

Using the above procedure, from approximately 1970 until early 2000 EPA conducted the 511 test program to test retrofit devices at the request of device makers. During that period, EPA's portion of the emissions testing (at the NVFEL) was provided at no charge to the applicant. EPA's NVFEL tested more than 100 retrofit devices that claimed to improve fuel economy; Table 1 categorizes these devices by type.[17] As shown, most were claimed to improve fuel economy by better preparing gasoline or the gasoline-air mixture for more-efficient combustion. Others claimed to reduce parasitic losses. Some attempted to modify driver behavior to operate the vehicle using fuel-efficient driving techniques.

Table 1. General Categories of EPA-Evaluated Aftermarket Devices (501 Testing)

General Device Category (Approximate Number Evaluated by EPA)	General Approach / Mechanism to Improve Fuel Economy	Specific Approach / Mechanism to Improve Fuel Economy
Air Bleed Devices (17)	Modify air-fuel ratio for leaner combustion	Bleeds air into carburetor; typically installed in PVC ventilation line or to replace idle mixture screw.
Vapor Bleed Devices (9)	Modify air-fuel ratio for leaner combustion	(Similar to the air bleed devices, except induced air is bubbled through water / antifreeze mixture)
Liquid Injection (2)	Modify air-fuel ratio for leaner combustion	Adds liquid into fuel-air intake system (not directly into combustion chamber)
Ignition Devices (7)	Unspecified (improve ignition quality to improve combustion)	Attaches to ignition system or used to replace original equipment ignition parts
Fuel Line Devices (heaters, coolers, magnets, metals) (12)	Improve fuel atomization / ionization / molecular structure or enhance fuel-air mixing to improve combustion	Heats (engine coolant, exhaust, electrical system), magnetizes, or ionizes fuel (dissimilar metals) before mixing with air
Mixture Enhancers (6)	Enhance mixing and/or vaporization of fuel to improve combustion	Mounts between carburetor and intake manifold, or entails general modifications to intake system
Internal Engine Modifications (3)	Make physical or mechanical function changes to the engine to improve efficiency	Deactivates cylinders in certain operating modes
Accessory Drive Modifiers (3)	Reduce parasitic losses to improve efficiency	Reduces power to specific automotive accessories
Fuels / Fuel Additives (13)	Improve fuel atomization and combustion	Improves combustion characteristics of fuel (added to gas tank)
Oils / Oil Additives (2)	Reduce engine frictional losses	Improves oil viscosity (poured into crankcase)
Driving Habit Modifiers (4)	Modify driver's behavior to drive in fuel-efficient modes	Directs driver to reduce acceleration, shift gears, turn off engine, etc.
Miscellaneous (12)	(Various approaches)	(Various approaches)
Source: Federal Trade Commission, http://www.ftc.gov/bcp/edu/pubs/consumer/autos/aut10.shtm		

Out of roughly 100 retrofit devices tested over the course of three decades, EPA's 511 testing team found that approximately five devices provided small fuel economy improvements without causing any detectable increases in exhaust emissions. Some devices were found to increase emissions, reduce fuel economy and/or harm the vehicle's engine. EPA's website summarizes the results of its 511 Program testing by stating that "Very few manufacturers have applied for this program in the past 10 years. Most devices tested in earlier years had a neutral or negative effect on fuel economy and/or exhaust emissions."[18]

[17] Federal Trade Commission, ""Gas Saving Products: Fact or Fuelishness?"", accessed online at: http://www.ftc.gov/bcp/edu/pubs/consumer/autos/aut10.shtm

[18] EPA, "Devices and Additives to Improve Fuel Economy and Reduce Pollution – Do They Really Work?", accessed online at http://www.epa.gov/otaq/consumer/420f11036.htm.

Important Note: nearly all of the devices tested under EPA's 511 program were designed for older vehicle technologies (e.g., engines using now-obsolete mechanical carburetors or early generation electronic fuel injection systems). Today's late-model gasoline LDV technologies are equipped with sophisticated on-board computers, electronic systems such as multiport fuel injection, closed-loop emissions control, and on-board diagnostics. Section 2.6 provides further discussion of fuel economy retrofit technologies designed specifically for late-model LDVs, and the associated opportunities to achieve fuel economy improvements.

2.1.1.3 Current Status of EPA's 511 Program

EPA conducted voluntary 511 testing of fuel economy retrofit devices up until late 1999. As noted, this testing was conducted at tax payers' expense. However, EPA management concluded that the provision of free emissions testing was too resource intensive and no longer justifiable. In part, this was because the many devices tested to date had demonstrated little or no fuel economy benefit. In May 2000, EPA put out a new publication about the 511 testing program; this included notice that EPA would no longer pay for confirmatory testing at EPA's NVFEL. The EPA publication estimated it would cost vendors a "minimum" of $27,000 (in 2000 dollars) to have the necessary confirmatory testing conducted at EPA. Going forward, device manufacturers would need to pay approximately twice as much for emissions testing under the 511 program (i.e., testing at both an independent lab and EPA's NVFEL).

Officially, EPA's 511 retrofit device testing program still exists. However, it appears to be dormant (in terms of industry interest); no device manufacturers have requested EPA testing for more than a decade. This may be because no obvious benefits exist for device manufacturers to seek EPA testing. First, EPA does not endorse or certify devices tested through the program. Second, the 511 protocol entails high costs (double testing), and it poses significant risks for the manufacturer (e.g., testing could result in EPA discovering that a device increases emissions). Third, manufacturers can apply for device "approval" from the California Air Resources Board (CARB). EPA accepts completion of the CARB process (described below) as evidence that a given device will not violate anti-tampering requirements or increase emissions levels when installed on in-use motor vehicles.[19]

Notably, in 2005 EPA did conduct preliminary confirmatory testing on one fuel economy retrofit device; this was done at the request of the Federal Trade Commission (FTC). Specifically, EPA performed emissions and fuel economy testing on two LDVs retrofitted with the "Super FUELMAX" device. The test vehicles were two Chevy Cavaliers (2002 and 2003 model years) equipped with 2.2 liter four-cylinder engines and automatic transmissions. The maker of the device was claiming a fuel economy increase of 27% using a set of two "neodymium" magnets that supposedly improved gasoline combustion. Based on this preliminary confirmatory testing, EPA concluded that "the Super FUELMAX device has no effect on fuel economy or exhaust emissions," and declined to conduct further testing on the device.[20]

However, FTC went beyond EPA by taking legal action on the company selling this device. FTC's jurisdiction (consumer fraud and false marketing claims) differs from EPA's (air quality and

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[19] This subsection is based on information obtained by TIAX during a personal communication with EPA staff, June 6, 2012.

[20] EPA, "Emissions and Fuel Economy Effects of Super FUELMAX: Preliminary Analysis," October 4, 2005, accessed online at http://www.epa.gov/otaq/consumer/devices/ftc_fuelmax_analysis1.pdf.

emissions integrity). According to an FTC press release in 2006, the company settled FTC's lawsuit for $4.2 million, and is now banned from selling or manufacturing the device in the U.S.[21] This type of enforcement action sends a loud and clear message to manufacturers of retrofit devices about claims they make. This FTC enforcement case appears to have involved a particularly egregious case of consumer deception, as the manufacturer was claiming that the Super FUELMAX device provides a 27% reduction in fuel use, compared to EPA 511 testing that showed no fuel economy improvement.

2.2 California ARB Oversight and Testing for Retrofit Devices

CARB currently implements motor vehicle air pollution laws and regulations in California; 13 other states have adopted CARB regulations, and six other states are reportedly considering their adoption. This oversight includes aftermarket retrofit devices (as well as alternative fuel conversion kits, Section 3). CARB classifies aftermarket motor vehicle parts into four basic categories: 1) replacement parts, 2) legal add-on or modified parts, 3) competition or racing parts only, and 4) catalytic converters.[22]

The following are more-detailed categories of aftermarket devices that vendors typically seek to market in California, pending approval by CARB:

- Air filter/intake/intake manifold modifications
- Aftertreatment devices, i.e., lean NO_x catalyst, improved catalyst formulations
- Engine Control Unit (ECU) reprogramming or reflashing
- Electronic engine governor/revolutions limiter
- Exhaust system/exhaust modification
- Fuel injection system/fuel injectors
- Fuel catalyst or fuel line modifications
- Ignition system/ignition system modifications
- Supercharger system/supercharger modifications
- Timing control/camshaft/rocker arm
- Turbocharger system/turbocharger modifications
- Vapor or water injection

These various types of aftermarket devices and vehicle modifications are typically intended to increase vehicle performance or fuel economy. CARB invokes California Vehicle Code Section 27156 (as well as the federal Clean Air Act) to prohibit sales of such devices or modifications if they will increase emissions of certified motor vehicles. To assess this potential, CARB requires that all aftermarket devices and vehicle modifications undergo an engineering evaluation before they can legally be sold in California. Generally, actual emission testing is not required. If the engineering evaluation determines that the proposed device or modification will not increase

[21] U.S. Federal Trade Commission, "FTC Halts Bogus Claims for 'Fuel Saving' Device," 2006 press release, accessed online at http://www.ftc.gov/opa/2006/08/savegas.shtm.

[22] California Air Resources Board, Aftermarket, "Performance and Add-On Parts," accessed online at http://www.arb.ca.gov/msprog/aftermkt/aftermkt.htm

vehicle emissions, it is granted an exemption to California's emission control system anti-tampering laws.

Important Note: the CARB requirement appears to prohibit a significant increase in any / all regulated pollutants, even if their levels remain below the applicable certification standards. The exact wording on CARB's application for approval[23] is:

"Manufacturers must present sufficient information to establish that an emissions increase will not result from the use of an add-on or modified part. If your device or modification is exempted, the Air Resources Board will issue an Executive Order stating that the part will not adversely affect emissions and that it is legal for sale and use in California."

In addition, the applicant (device manufacturer) must sign an "Emission Statement" that includes the following clause, which seems to prohibit new emissions of **unregulated air toxics**.

"I affirm that to the best of my knowledge this device shall not cause the emission into the ambient air of any noxious or toxic matter that is not emitted in the operation of such motor vehicle without such device."

CARB's issuance of an Executive Order (EO) allows a retrofit device to be sold in California (or other CARB jurisdictions) and installed on specific vehicles / engine families. Issuance of an EO "does not constitute a certification, accreditation, approval, or any other type of endorsement by the Air Resources Board of any claims concerning alleged benefits of a device." Moreover, "no claims of any kind concerning anti-pollution benefits may be made for an exempted device." To control the integrity of this process, CARB assigns every EO-approved retrofit device a number that can be verified by Smog Check stations, BAR Referee stations, or CARB inspectors.

Important Note: the EPA and the CARB processes (described above) to legally sell fuel economy retrofit devices are NOT APPLICABLE to devices designed to reduce a vehicle's emissions or convert it to an alternative fuel. Alternative fuel conversion systems (Section 3) must undergo EPA's or CARB's much more complex and costly "Certification" processes, which are described in Section 4. In addition, both EPA and CARB have complex, costly "verification" requirements for the sale of emissions control retrofit devices, which today are primarily offered for heavy-duty diesel engine vehicles (e.g., diesel particulate filters).

2.3 Focus on Retrofit Strategy to Reprogram LDV Engine Control Units

Potentially, major societal benefits can be realized from retrofit devices that can cost effectively improve the fuel economy of America's in-use LDVs. However, as further described in this report, there are challenges associated with developing and deploying such devices; these include concerns that they may violate EPA / CARB prohibitions against tampering[24] and/or void the converted vehicle's manufacturer warranty. This section further evaluates the potential of one

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[23] California Air Resources Board, "Application Forms for Exemptions for Add-On or Modified Parts (VC 27156), Form A," accessible on CARB website at: http://www.arb.ca.gov/msprog/aftermkt/forms/forms.htm.

[24] According to EPA and the Clean Air Act, any instructions that request vehicle operators to "adjust the air/fuel ratio", or "adjust a knob and listen for the engine to misfire, referred to as feeling vibrations or stuttering, are in violation of the prohibition against tampering." In fact, installation of many popular devices (e.g, those that retard ignition timing) or even following installation instructions may be considered tampering. See EPA's website at: http://www.epa.gov/otaq/consumer/420f11036.htm.

particular technical approach to retrofitting late-model gasoline LDVs for improved fuel economy. Specifically, it looks at opportunities and challenges associated with retrofit strategies that modify the computer programming of LDVs.

2.3.1 Overview of ECU Purpose and Technology Evolution

Engine Control Units (ECUs; also called Engine Control Modules, or ECMs[25]) are the compact "brains" of modern vehicles; they include a microprocessor, built-in random access memory (RAM), signal-conditioning chips (for sensor inputs), output transistor/drivers (for actuating ignition coils and fuel injectors), and memory chips (for calibration purposes). The ECU and its various subsystems provide precise air and fuel metering, enable very sophisticated on-board diagnostics capabilities, and also control various power train functions. ECUs are essential for today's LDVs to meet very low emissions levels and provide optimized fuel efficiency for a given power output and performance level.

Aftermarket products exist today that provide relatively simple ways to reconfigure ECUs, purportedly to improve LDV fuel economy and/or performance. For example, some companies sell hand-held devices that "reflash" the ECU and thereby claim to improve fuel economy. In reality, re-tuning an in-use vehicle's engine by this (or other) means to increase fuel economy presents challenging engineering tradeoffs. For example, increased mileage can come at the expense of reduced vehicle performance (horsepower and/or torque) or a shortened life for exhaust emission control system components (such as three-way catalysts). The remainder of this section provides an overview of relevant ECU technology, and describes specific tradeoffs and challenges associated with modifying OEM configurations.

An LDV's ECU microprocessor includes embedded software with coding that controls engine and powertrain functions. Using this software, the ECU initiates ignition primary dwell and actuates spark output, regulates fuel injector activity, controls the EGR valve, and other functions. The ECU microprocessor obtains certain engine-specific parameters and information (spark ignition timing, fuel injector activity, exhaust gas recirculation rate, etc.) by reading information from the memory chips, which contain proper "tuning" information for each specific engine.

Memory chip technology has undergone major evolution over the last two decades. The first type of memory chip used in automobiles was Programmable Read-Only Memory (PROM). PROMs could only be programmed once, restricting any future changes to the ECU. Therefore, if a different engine calibration or an update was required, it was necessary to replace the old PROM with a new one containing the new calibration information.

In the early 1990s, advances in technology resulted in the EPROM (Erasable Programmable Read-Only Memory). However, erasing the information required the microprocessor to be physically removed from the vehicle and placed under an intense ultraviolet light source. Once the information was deleted, the chip could be reprogrammed using a special system. Although EPROMs were an improvement compared to PROMS, the reprogramming process remained tedious.

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[25] ECU and ECM are often used interchangeably, and sometimes the term "power control module" (PCM) is also used in reference to the powertrain controller. For the purposes of this report, "ECU" refers to the device that controls both engine and transmission. (Source: National Instruments, www.ni.com).

As technology continued to evolve, the next improvement was the EEPROM (Electronically Erasable Program Read-Only Memory) chip. These initially appeared in 1996 on LDVs equipped to meet "OBD II" requirements. EEPROMs could be recalibrated without being removed from the vehicle. With this technology, a scan tool is hooked up to the diagnostic port of the vehicle, and used to electronically erase the EEPROM, followed by reprogramming with a new software calibration. This process proved to be much quicker and simpler than previous processes; moreover, it eliminated many potential points of failure and error.

Flash-PROMs comprised the next generation of memory chips. The main differences between Flash-PROMs and EEPROMs are their respective data storage capabilities and the speed and accuracy of programming. Flash technology enables faster programming because it can erase and reprogram the entire chip all at once. Reprogramming the page in a single step eliminates another potential source of programming error.

2.3.2 Typical Objectives for Reprogramming ECU

Reprogramming of a late-model LDV's ECU – aka "reflashing" of its Flash-PROM chip – may be performed by the OEM's authorized service arm for a variety of reasons. For example, false trouble codes may occur on a vehicle and require fixing. The original factory programming may be overly sensitive, and may not take into account wear or other factors that may affect the operation of certain sensors or the OBD II monitors. Reflashing could also be necessary to change engine idle speed, spark timing, fuel mixture or other emission control functions. It may be required to resolve a hot or cold starting issue, idle roughness, engine stalling, or an emissions failure. Software changes may also be necessary to smooth out or change the shift characteristics of an automatic transmission; to modify ABS operation, traction control or stability control systems; to change steering feel on vehicles with variable assist steering; or to change settings for vehicles with electronic ride control. Before authorizing reflashing of in-use vehicle ECUs, OEMs are technically required to obtain approval from EPA and/or CARB (e.g., file for a "Running Change"), if the modification has potential to affect emissions.[26]

The above primarily describes situations in which vehicle OEMs might need to reprogram or reflash LDV ECUs, to meet specific needs for their customers' in-use vehicles. The technique of reprogramming / reflashing is also used by end users or aftermarket providers; typically, the objective is to improve vehicle performance. For example, more engine horsepower can be obtained by enriching the air-fuel ratio (providing more fuel per volume of air) and/or increasing boost pressure (on turbocharged and supercharged engines). Software reflashing is also used under the objective of improving fuel economy rather than increasing performance. Further discussion is provided in subsequent sections.

2.3.3 Estimated U.S. Population of In-Use LDVs to Potentially Retrofit

TIAX attempted to obtain verifiable estimates for the number of late-model in-use LDVs in the U.S. LDV fleet that could potentially receive cost-effective computer reprogramming for improved fuel economy. Such information involves complex assumptions and inputs, some of which may be proprietary. For example, it is not known which LDV models and vintages contain

[26] Personal communication between TIAX staff and senior CARB staff member, June 2012.

the types of "flash-reprogrammable" computer memory (see Section 2.3.1) that would be most conducive and desirable to upgrade.

Obtaining hard numbers was not within the scope of the project, but the universe of potential software upgrades can be roughly bounded. Assume that 20% of the currently deployed 235 million LDVs are 2009 model year or newer. Such vehicles have at least 50 percent of their useful lives remaining, and therefore might warrant retrofitting.[27] This sub-population of in-use LDVs is therefore calculated to be approximately 47 million (235 million X 0.2). Next, assume low (25%), medium (50%), and high (75%) scenarios for how many 2009 or newer LDVs could receive software upgrades. This derives low, medium and high estimates of 11.75 million, 23.50 million, and 35.25 million LDVs, respectively, for the universe of potential U.S. LDVs that might be feasible to receive computer software upgrades. Expanding eligibility assumptions down to older in-use vehicles (e.g., the 2004 MY) will result in significantly larger numbers of LDVs that might make good candidates for retrofitting, although there will be tradeoffs with remaining useful life.

2.4 Potential Tradeoffs with Modifying LDV ECUs

The sections below describe potential tradeoffs associated with modifying the software programs of late-model LDVs. This is followed by discussion of an example aftermarket device, the Max Energy E-CON manufactured by Hypertech, which purports to improve fuel economy by reflashing the ECM of compatible LDVs.

2.4.1 Fuel Economy, Emissions and Engine Power

Engine air-fuel (AF) ratio for late-model gasoline LDVs is tightly controlled by the ECU, and varies according to engine speed and load. The stoichiometric AF ratio for such engines is 14.7:1. Peak fuel economy is obtained at AF ratios slightly leaner (higher) than the stoichiometric value. However, fuel efficiency is just one vehicle attribute around which the engine must be designed. The instantaneous AF ratio for each specific engine condition is generally programmed to provide an optimal combination of three attributes: 1) smooth and reliable power, 2) minimized fuel consumption, and 3) low emissions levels to satisfy EPA and/or CARB requirements. There are inherent tradeoffs associated with simultaneously achieving these objectives.

Given the various tradeoffs, the strategy employed by OEMs for modern gasoline-fueled LDVs has been a stoichiometric air-fuel ratio. This enables use of a three-way catalyst, which is the universally equipped exhaust aftertreatment technology for today's gasoline LDVs. Only under stoichiometric conditions can three-way catalysts simultaneously oxidize carbon monoxide (CO) and unburned hydrocarbons (UHC) to carbon dioxide (CO_2) and water (H_2O), respectively, while also reducing nitrogen oxides (NOx) to nitrogen (N_2).

Theoretically, a "retrofittable" approach to improving fuel economy might be to reprogram the engine for a leaner air-fuel mixture. In part, spark-ignited internal combustion engines (ICEs) operate most efficiently in a lean condition because it reduces "throttling losses." In a typical gasoline ICE vehicle, power output is controlled frictionally using a common throttle for all

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[27] The typical replacement cycle for passenger cars and light trucks in 2009 was approximately 6 years, according to Autoobservercom. See http://www.autoobserver.com/2009/02/car-owners-hanging-onto-their-current-rides.html.

cylinders. The greatest relative fuel efficiency of the engine is obtained when the throttle is wide open. As the throttle valve is closed to reduce power output, the engine must work harder to pump the air-fuel mixture into the cylinders, increasing frictional losses. If the AF ratio is "leaned" out (operated with excess air), then partial load (lower power) driving modes can be achieved with the throttle closer to fully open. This increases efficiency during normal driving, which occurs below the maximum power and torque capability of the engine.[28]

Actually pursing such a retrofit strategy presents challenges, however. As noted above, OEMs must design their engines to meet and maintain exhaust emissions requirements, including the need to achieve sufficient useful life for emissions control equipment such as the three-way catalyst.[29] To maintain low emissions and extend catalyst life, AF ratios must be kept at (or close to) stoichiometric, with periodic incursions into the rich region.[30] Another factor that favors stoichiometric combustion is related to fuel flammability, defined as the fuel's ability to burn within the cylinder. If the air-gasoline mixture is too lean, the flame will lack sufficient speed to propagate across the cylinder per the engine's instantaneous need, or the flame front will not propagate at all. If the flame fails to propagate a cylinder "misfire" will occur, leaving the catalyst to oxidize (burn) excessive amounts of unburned fuel, which can lead to catalyst overheating and failure. In this condition, all three parameters (emissions, efficiency, and performance) would be negatively impacted.

In other words, engines in today's late-model gasoline LDVs operate primarily at the stoichiometric AF ratio more for emissions reductions and emissions control system durability, trading off optimum fuel efficiency. To control and maintain the AF ratio at the stoichiometric point, the LDV's ECU monitors multiple inputs from different sensors and devices such as the MAP (Manifold Absolute Pressure), TPS (Throttle Position Sensor), MAF (Mass Air Flow), ECT (Engine Coolant Temperature), IAT (Intake Air Temperature) and oxygen sensors. If the AF ratio is leaned out beyond what the program requires, the ECU goes into "Open Loop" mode and overrides inputs from the sensors. It will revert to "look-up tables" (multi-dimensional performance maps) for its source of information, and then typically a trouble code will be set. The ramifications of this will depend on the specific driving and engine conditions, but open loop operation would normally be very short in duration.

Theoretically, increased use of exhaust gas recirculation (EGR) may also present opportunity to retrofit modern in-use LDVs for improved fuel economy. Spark-ignited gasoline engines of today's LDVs can operate with greater efficiency through the use of EGR. According to at least one expert, using EGR in gasoline engines has the same effect as raising the gasoline's octane content, thereby "suppressing knock, allowing more advanced spark timing and higher compression ratios, and ultimately allowing the engine to operate more efficiently." In addition, EGR reduces throttling loss in gasoline engines at part load, "offering another fuel economy advantage." If performance and other tradeoffs can be managed, the fuel efficiency benefits of

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[28] Marc Ross, "Fuel Efficiency and the Physics of Automobiles," Physics Department, University of Michigan, originally published in Contemporary Physics 38, 1997, updated in 2004, accessed online at: http://sitemaker.umich.edu/mhross/files/fueleff_physicsautossanders.pdf

[29] Durability requirements for emissions control system components for new vehicles can be as high as 150,000 miles under CARB regulations, depending on various factors.

[30] LDV OEMs use a fuel enrichment strategy for gasoline engines at fuel load, to protect the catalyst. This reduces exhaust temperatures when the catalyst would otherwise be most vulnerable. It also helps to prevent pre-ignition (knocking). EPA and CARB allow such rich operation in LDVs because it's limited and necessary to protect the emissions control system. See SAE Engineering Online at: http//www.sae.org/mags/SVE/11012.

EGR at full load can be very large, because there is significantly less need to run rich. In addition, the lower temperatures help to avoid heat transfer energy losses, providing more of the car's energy for motive power. [31]

This implies that increasing the level of EGR under full load could be one approach to improving the full economy of late-model in-use LDVs. Specifically, if the ECU can be reprogrammed to increase EGR rate at full load, gasoline will be less prone to pre-ignition (knock). This in turn affords greater control over the precision of the engine's timing through ECU retrofit strategies. However, fuel control and EGR are very interactive parameters on modern LDVs; modifying one can create complex tradeoffs with the other.[32] As further discussed, the viability of such strategies would depend on the ability and cost to manage these tradeoffs.

2.4.2 Vehicle Warranty

As with any change to the OEM's vehicle, the installation of any device or software that alters stock ECU equipment or its calibration can potentially void the OEM's vehicle warranty. There are numerous reasons to make this conclusion. The following OEM stance on the subject is typical. The 2012 Nissan Warranty Information Booklet[33], clearly states that its warranty does not cover damage, failures or corrosion resulting from or caused by:

- *Alteration, tampering, or improper repair.*
- *Installation of non-Nissan approved accessories or components.*
- *Improper installation of any Nissan approved aftermarket accessory or component.*
- *A vehicle whose odometer mileage has been altered, or the odometer repaired or replaced and the actual vehicle mileage cannot be correctly and readily determined.*

The 2012 Ford F-150 owner's manual states that the following conditions will void the vehicle warranty (bolded text emphasis added):

> *The installation or use of a non-Ford Motor Company part (other than a certified emissions part. or any part (Ford or non-Ford) designed for off-road use only installed after the vehicle leaves the control of Ford Motor Company, if the installed part fails or causes a Ford part to fail. Examples include, but are not limited to lift kits, oversized tires, roll bars, cellular phones, alarm systems, automatic starting systems and **performance-enhancing powertrain components or software and performance "chips."***

CARB, in Executive Order #EO-D-260-14 issued for the Energy Max ECON developed and marketed by Hypertech Inc., states that:

> "*This Executive Order does not constitute any opinion as to the effect the use of the Max Energy, Max Energy ECON, and the HyperPAC may have on any warranty either expressed or implied by the vehicle manufacturer*".

[31] Thomas Reinhart, Engine Design & Development Department, Southwest Research Institute, quoted in SAE Engineering Online, accessed on May 31 at http://www.sae.org/mags/SVE/11012

[32] Personal communication between TIAX staff and a senior CARB engineer, June 2012.

[33] Available online at http://www.nissanusa.com/content/dam/nissan/pdf/techpubs/2012/2012_N_WIB.pdf (page 8)

And finally, the device manufacturer (Hypertech) advises the following to end users when getting a modified vehicle serviced[34]:

> ***"Return Your Vehicle to Stock Tuning** BEFORE taking your vehicle in for service. If you take your vehicle to a dealer or mechanic for service, you must first remove the Hypertech Power Tuning and restore the stock programming. This is because diagnostic devices expect to find stock calibrations and will often overwrite the program if the latest stock calibration is not found in the computer's memory. This will result in the loss of your Hypertech Power Tuning data. The Power Tuning can be easily removed to restore the stock tuning before you take your vehicle in for service, enabling the service technician to upgrade your stock calibrations. After the service is complete, you can reinstall your Hypertech Power Tuning."*

On the other hand, as pointed out by the automotive-enthusiast authority Edmunds.com, there is a "great deal of gray area" with regard to whether or not simply installing an aftermarket part or modifying your vehicle can legally void your warranty. The following quotes are taken from an Edmunds.com article published in 2009[35]:

> *"Some dealerships may say 'just because you have a [cold air] intake or something' that the whole vehicle warranty is voided," explains Loren Wong, Edmunds associate business analyst and a former warranty administrator for BMW and Acura. "That's not true."*
>
> *The saving grace for consumers is the Magnuson-Moss Warranty Act of 1975. The act states that a dealer must prove that aftermarket equipment caused the need for repairs before it can deny warranty coverage. However, if the reason for a parts failure is unclear, a dealer will usually charge you to diagnose the vehicle. If the aftermarket part was not properly installed or a modification led to a component failure, it is within the dealer's right to void the warranty for that part, and you will have to pay for the repairs out of pocket. If the aftermarket parts had nothing to do with the repairs in question, you will be refunded the fee for the diagnosis.*
>
> *Warranties are open to interpretation: If you feel that a service advisor has denied your warranty claim unfairly, you can always go higher up in the management chain, contact the automaker directly or go to another dealer altogether."*

2.5 Summary of ECU-Related Fuel Economy Retrofit Strategies

A retrofit approach to improve fuel efficiency of typical late-model LDVs might involve strategies such as those described below.

NOTE: These example retrofit strategies are not necessarily technically proven or legally viable. All strategies appear to present potential tradeoffs (emissions / tampering, fuel economy, performance, safety, OEM warranty, etc) that must be addressed and carefully managed, as discussed in other sections of this report.

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34 http://www.hypertech.com/support-FAQ.aspx

35 Edmunds.com, "What Voids Your Vehicle's Warranty?", 7/28/2009, online at http://www.edmunds.com/auto-warranty/what-voids-your-vehicles-warranty.html.

- Change the ECU range of acceptable air-to-fuel ratio values – This strategy could allow operation at higher (leaner) AF ratios while avoiding Open Loop operation. This could reduce throttle losses and improve fuel economy. It would involve software reprogramming only, i.e., no hardware changes would be required. This strategy might increase emissions of one or more regulated pollutants.

- "Trick" the ECU to accept lean fuel commands – This strategy involves reprogramming the ECU to perceive certain conditions from various sensors (e.g., high engine temperature, low load, or high intake air temperature) that call for lean fuel commands. In other words, it could eliminate fuel rich operations designed to minimize NOx and/or protect the catalyst. Because this could require alteration or replacement of certain sensors, there may be both software- and hardware-related components to this strategy. This strategy might increase emissions of one or more regulated pollutants.

- Reprogram the ECU to increase EGR rates under full load – This strategy involves modifying the ECU's control over the EGR system (EGR valve, solenoid, vacuum source, and EGR position sensor) to increase the rate of exhaust gas recirculation, allowing more-fuel-efficient operation at full load. In addition to software reprogramming, this strategy might require hardware component changes or modifications to increase EGR rates at optimum operating modes. This strategy might increase emissions of one or more regulated pollutants.

- Reprogram the ECU to proportionally reduce fuel and air – This strategy involves maintaining the stock ECU's air-fuel ratio for each driving condition, while reducing volumes of both fuel and air. Through software changes alone, this could potentially improve fuel economy without increasing exhaust emissions levels. However, a decrease in power output would result.

- Reprogram the ECU to promote more-fuel-efficient driving – This strategy involves software and/or hardware changes for the purpose of modifying how the driver operates the vehicle. For example, shift indicator light (SIL) technology, which has long been used by OEMs on certain new LDVs[36] with manual transmissions, can also be retrofitted to in-use vehicles. SILs sense engine speed and manifold vacuum (among other parameters), and send a signal (usually visual) to the driver to shift gears at the most fuel-efficient moment under the instantaneous driving conditions. EPA has valuated aftermarket SIL kits in the past and has found that they do not increase emissions of regulated pollutants. (No retrofit products of this type were found to be available during an internet check in May 2012.)

2.6 Example Fuel Economy Retrofit Device: Max Energy E-CONTM™

The Max Energy E-CON™ is a hand-held programming device manufactured and marketed by Hypertech Inc. (Bartlett, TN). It is designed to reprogram the engine and/or transmission control module of specified LDVs by modifying various operating parameters. (The fuel economy improvement strategy of the Max Energy E-CON™ most closely resembles the first approach described in Section 2.5 above.) The device downloads OEM calibration updates, non-emissions

[36] In part, SILs have been installed by OEM as strategies to achieve higher EPA fuel economy ratings on their vehicles. If the OEM demonstrates that a significant number of customers will actually use SIL feedback to shift the vehicle, the SIL schedule can be followed during the official chassis dynamometer fuel economy testing, thus achieving a higher fuel economy rating for the vehicle being certified.

related upgrades, and patches or fixes in the firmware; however, emission-related data files cannot be modified by the end user.

2.6.1 Granting of Executive Order / Emissions Tests Results

In October 2011, CARB granted Executive Order #D-260-14 authorizing sale of the Max Energy E-CON™ (and two other Hypertech retrofit devices) in California. Issuance by CARB of this EO effectively indicates that the device does not increase emissions levels when it is installed on approved vehicles. In this case, actual emissions tests were conducted by the vendor and cited by CARB in the EO. Specifically, the following six types of late-model LDVs were tested:

- 2010 5.4L Ford Expedition
- 2010 5.3L Chevrolet Tahoe
- 2010 5.7L Dodge Challenger
- 2009 4.0L Nissan Frontier
- 2008 5.4L Ford GT500
- 2007 7.0L Corvette

Emissions test results showed that levels of all regulated pollutants met the applicable standards when tested using the Cold-Start CVS-75 Federal Test Procedure (FTP) test cycle and the Supplemental Federal Test Procedure (SFTP-US06) test cycle. Since 1) emissions levels were shown not to increase (with statistical significance) and 2) Hypertech's installation instructions do not recommend tuning the vehicle to non-OEM specifications, CARB deemed this device legal for on-road use in California. Full provisions for use of the device are described within the CARB EO, which refers only to emissions tests results and does not discuss or list fuel economy results.

Notably, by emissions testing just six LDVs ranging from model year 2007 to 2010, Hypertech was able to obtain CARB's approval to market its Max Energy E-CON™ retrofit device to a very large cohort of vehicles found in today's in-use LDV fleet. As listed in Exhibit A of the EO, the device is "exempt" from California vehicle code anti-tampering prohibitions when installed on hundreds of LDV makes and models that span model years 1996 to 2011.

Like other EO's of this type, CARB states the following regarding the Hypertech device:

> *"This Executive Order does not constitute a certification, accreditation, approval, or any other type of endorsement by the air resources board of any claims of the applicant concerning anti-pollution benefits or any alleged benefits"*.

On certain EOs, CARB also states that it "reserves the right to conduct additional emissions tests in the future." If such tests demonstrate higher emissions including under "off-cycle" conditions, or provide CARB with "reason to suspect" that the retrofit device will affect durability of the emissions control system, CARB will require the device manufacturer to submit new emissions and durability data, or will conduct its own compliance testing.[37]

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[37] CARB, accessed online at http://arb.ca.gov/msprog/aftermkt/devices/eo/D-260-10.pdf

2.6.2 Uncertainty of Fuel Economy Improvement Claims

The best way to corroborate any changes in fuel economy and/or engine power output attributable to a given aftermarket device is to conduct chassis dynamometer testing (pre- and post-conversion) under controlled conditions using standardized test cycles. That procedure was apparently followed at the two laboratories hired by Hypertech to conduct emissions testing on the Energy Max E-CON™. Hypertech's website reports a 13.7% fuel economy increase after installing the device on a Ford Crown Victoria, per testing conducted at Automotive Testing Laboratories (see next subsection). TIAX contacted Automotive Testing Laboratories as well as the other testing lab to obtain more information about effects of the Energy Max E-CON™ on fuel economy, power, and/or emissions. Technical representatives of both laboratories were not able to share information due to non-disclosure agreements with the device's manufacturer.

TIAX also contacted Hypertech to inquire about the fuel economy tests and results at these labs. A Hypertech representative declined to provide additional information, noting that laboratory testing of LDVs on chassis dynamometers may not be representative of real-world driving conditions, and variation (e.g., driver-to-driver, vehicle conditions) occurs even in real-world use. The representative noted that Hypertech prefers to market its products by publishing user reviews rather than showing laboratory tests results. All user reviews posted on the Hypertech website[38] (as of April 2012) claim higher performance after installing Hypertech's various devices. Some reviewers claim higher power output and/or higher mileage.

From an engineering perspective, no basis exists to conclude that reprogramming an LDV's ECU can deliver increased horsepower while simultaneously improving fuel economy. Reprogramming a typical late-model LDV's ECU could potentially increase its fuel economy, but this could occur at the expense of: (1) limited or reduced engine power output, and/or (2) reduced lifetime of the vehicle's three-way catalyst. Moreover, any effect on mileage and power output might be difficult for the driver to perceive, due to many variables involving parameters such as individual driving skills, fuel and vehicle variations, and road conditions.[39] For these reasons and others, user testimonials do not represent substantial proof that fuel economy improvements and performance enhancements can both result from installing aftermarket devices such as the Hypertech Max E-CON™ device.

NOTE: Precedence exists for the federal government to challenge claims about fuel economy retrofit devices, and assess large penalties against manufacturers making claims that are found to be false or unsubstantiated. Refer back to Section 2.1.1.3 for discussion about a specific lawsuit filed by the Federal Trade Commission.

2.6.3 Cost to Consumers and Simple Payback

TIAX contacted an authorized seller of the Energy Max E-CON™ device to ascertain its capital and installation cost. Table 2 summarizes the price quote received from a dealer in Temple City, California;[40] these costs to consumers are believed to be typical.

[38] User reviews available at: http://www.hypertech.com/user-reviews.aspx

[39] U.S. Department of Energy at http://www.fueleconomy.gov/feg/why_differ.shtml

[40] Source / dealer: Advance Speed Shop, Temple City, CA, 626-279-7986.

Table 2. Dealer quote for capital and installation costs of Energy Max E-CON™

Capital Cost (with tax)	$359.10
Shipping	$15.00
Installation*	$0.00
Total Cost	**$374.10**

***According to the dealer, the device is "easily installed" by the vehicle owner / end user. However, the $0 installation cost does not account for installation time invested by the owner / end user.**

Using these capital costs, TIAX evaluated the simple payback period in reduced fuel costs that could be gained from using the Energy Max E-CON™ device. TIAX used Hypertech's data from Automotive Testing Laboratories indicating that a Ford Crown Victoria's fuel economy increased from 18.42 to 20.94 mpg (13.7%) after installation of the device. As shown below, if this information is accurate and representative, the cost of the Energy Max E-CON™ device can be paid back from fuel savings within about one year, assuming $4.00 per gallon gasoline and 15,000 annual miles traveled. With gasoline at $3.50 per gallon, the payback period would take proportionally longer (but less than two years). Typically, fleets seek a payback period of three years or less to justify investing in vehicle technologies that reduce fuel costs.[41]

Hypertech Max Energy E-CON™ Economy Power Programmer

Lab Test: Automotive Testing Laboratory in Mesa, Arizona
Vehicle: Ford Crown Victoria

TUNING	TEST AVERAGES
Stock	18.42 MPG
Hypertech	20.94 MPG

	Without Device	With Device		Gasoline Price per Gallon						
Miles per Year	**Gallons Used per Year**	**Gallons Used per Year**	**Gallons Saved per Year**	**$3.50**	**$3.75**	**$4.00**	**$4.25**	**$4.50**	**$4.75**	**$5.00**
10,000	543	478	**65**	$ 228.7	$ 245.0	$ 261.3	$ 277.7	$ 294.0	$ 310.3	$ 326.7
15,000	814	716	**98**	$ 343.0	$ 367.5	$ 392.0	$ 416.5	$ 441.0	$ 465.5	$ 490.0
20,000	1,086	955	**131**	$ 457.3	$ 490.0	$ 522.7	$ 555.3	$ 588.0	$ 620.7	$ 653.3
25,000	1,357	1,194	**163**	$ 571.7	$ 612.5	$ 653.3	$ 694.2	$ 735.0	$ 775.8	$ 816.7
30,000	1,629	1,433	**196**	$ 686.0	$ 735.0	$ 784.0	$ 833.0	$ 882.0	$ 931.0	$ 980.0
35,000	1,900	1,671	**229**	$ 800.3	$ 857.5	$ 914.7	$ 971.8	$1,029.0	$1,086.2	$1,143.3

Investment recovered during the first year

Figure 1. Simple Payback for Energy Max E-CON™ Device (Source: Hypertech website).

2.7 Logistics and Issues Bringing Retrofit Technologies to Market

In this task, TIAX broadly reviewed the barriers and challenges associated with selling aftermarket retrofit devices in the United States that seek to improve motor vehicle fuel economy. Generally, barriers and challenges seem to fall into the following categories: 1) keeping manufacturing costs down, 2) complying with anti-tampering requirements of EPA and/or ARB; 3) maintaining viability of the vehicle's OEM warranty; and 4) proving that the

[41] Input received by TIAX from surveying a wide array of fleets in preparation of a major report on natural gas vehicles, 2011.

device cost-effectively reduces fuel usage without unacceptable tradeoffs in other vehicle attributes. These are expounded upon throughout this report; a brief summary for each category is provided below in the context of one specific device that was reviewed, the Energy Max E-CON^{TM}.

2.7.1 Costs of Manufacturing and Marketing ECU Reprogramming Kits

No data are currently known about the costs incurred by aftermarket companies such as Hypertech to develop and market fuel economy kits that reprogram or reflash ECUs of late-model LDVs. Because such retrofit systems are neither 1) emissions reduction devices nor 2) alternative fuel conversion systems, they are not required to undergo the rigorous and costly certification processes of EPA and/or CARB (see Section 3). Consequently, the total costs of manufacturing a fuel economy retrofit device such as Hypertech's Max Energy E-CON^{TM} can be relatively low compared to an emissions reduction retrofit or fuel conversion device. This appears to be reflected in the affordable per-unit selling price of the Max Energy E-CON^{TM} (about $375) and its pay back period. Still, testing requirements to prove that emissions levels will not be increased can be expensive (up to $100,000), and must be amortized across sales of many units.

2.7.2 Navigating Anti-Tampering Requirements

Of paramount concern for manufacturers of fuel economy retrofit devices is how to successfully navigate anti-tampering requirements. The definition of what constitutes tampering under EPA and CARB regulations appears to boil down to a performance standard, coupled with certain hard prohibitions. Apparently, any retrofit device that significantly increases the emissions of a certified vehicle (however defined) cannot be considered exempt from anti-tampering requirements, and will not be approved. Also, it appears that by definition certain modifications (e.g, adjusting the idle mixture) constitute tampering, and are prohibited from being included in retrofit kits sold in the U.S. With specific regard to retrofit strategies that reprogram /reflash the ECU of a light-duty LDV, whether or not this constitutes tampering seems to depend on the specific software (and hardware, if applicable) changes that are utilized.

The Energy Max E-CON^{TM} device, which uses this general ECU-reflash strategy, serves as a useful example. Through a combination of emissions testing (paid for by the manufacturer) and engineering evaluation, the device was found by CARB to not increase emissions or involve any process that defeats the base vehicle's emissions controls. By issuing EO #D-260-14 (most recently in October 2011) for the Energy Max E-CON^{TM} device, CARB has certified that installing it on approved vehicle types using the recommended procedure does not constitute tampering. Specifically, issuance of the EO exempts both the manufacturer and end user from federal and state anti-tampering provisions. Furthermore, since EPA accepts CARB-issued EOs as proof of compliance with federal requirements, properly installing this particular device on an approved EPA-certified vehicle is deemed legal and exempt from anti-tampering provisions.

2.7.3 Maintaining Viability of the OEM Warranty

As noted previously, the installation of any device or software that alters stock ECU equipment or its calibration can potentially void the OEM's vehicle warranty. This remains a gray area for end users. Based on typical language from owner's manuals, most OEMs warn their customers that such modifications will void the vehicle's OEM warranty. However, other sources (e.g., Edmonds.com) cite the Magnuson-Moss Warranty Act of 1975, which states that warranty coverage cannot be denied unless there is proof that aftermarket equipment caused the need for repairs. This leaves potential end users in an undefined, somewhat risky position. For example, if problems do arise on retrofitted vehicles, the costs to diagnose the problem may fall on the end user. Improper installation of the retrofit device can be invoked as the cause of the OEM part failing; this is not easily disproved. The end result may be that the end user pays for repairs out of pocket that would otherwise be covered under warranty.

2.7.4 Marketing Challenges

A potential challenge for marketing any new fuel-economy-improvement retrofit involves how to convince potential end users that the device can deliver a satisfactory payback period. The previous section showed that the cost of purchasing and installing the Energy Max E-CON™ device can be paid back from fuel savings within about one year, based on $4.00 per gallon gasoline, 15,000 annual miles traveled, and zero installation cost (i.e., the user installs the device). A key assumption is that the fuel economy benefit claimed by the manufacturer (13.7%) is both accurate and representative of LDVs that can utilize this particular device. As noted, TIAX was NOT able to corroborate the device's claimed fuel economy benefits from the manufacturer, Hypertech Inc., or from the two laboratories where testing was performed.

Obtaining government-sanctioned or independent data can be both expensive and elusive. EPA will analyze these types of devices under its voluntary Aftermarket Retrofit Device Evaluation ("511") Program, but does not approve, certify, endorse, or register any products evaluated through this program. Over the past three decades, the EPA has evaluated more than 100 devices that claim to increase the fuel economy of vehicles on which they are installed or implemented. CARB has also extensively tested or review testing of such devices. Neither agency appears to have found definitive proof that aftermarket devices improve fuel economy in a way that is significant, provable, and does not increase emissions levels. Moreover, both EPA and CARB actively encourage skepticism when it comes to purchasing aftermarket devices that claim to improve fuel economy. In sum, assuming a given retrofit device can provide verifiable cost-effective fuel economy improvements, the lack of a government (or independent third-party) rating system appears to be a barrier to its wide-scale commercial deployment.

Another marketing challenge for aftermarket devices is the need to avoid unacceptable tradeoffs with other vehicle attributes. As noted above, potential tradeoffs of fuel-saving retrofits might involve reduced vehicle performance, compromised vehicle safety, or anxiety about voiding warranty provisions. If these tradeoffs are not adequately managed by the device manufacturer, the result may be severely reduced ability to sell the product.

3. Assessment of LDV Conversions for Flex-Fuel Alcohol-Gasoline Operation

3.1 Introduction / Background

The federal government (U.S. Department of Energy) describes the aftermarket conversion of a vehicle for operation on an alternative fuel as:

> *"A vehicle or engine modified to operate using a different fuel or power source. Conventional vehicles and engines from original equipment manufacturers (OEMs) can be altered to run on fuels like propane, natural gas, or electricity."*[42]

Conceptually, the federal government acknowledges the legitimacy of such conversions to displace petroleum usage, based on the following statement:

> *"Many OEMs offer alternative and advanced vehicles. However, the availability of certain models, fuels, and technologies can vary. This makes vehicle and engine conversions a good option to explore as a way to reduce or eliminate petroleum use."*[43]

Flexible fuel vehicles (FFVs) are special types of alternative fuel vehicles; they are designed to operate on gasoline mixed with alcohol (up to 85%), or any mixture of the two. Two different alcohol-gasoline blends are technically and commercially viable alternative fuels for FFVs. These are 1) M-85, a blend of 85% methanol and 15% gasoline), and 2) E-85, a blend of 85% ethanol and 15% gasoline[44].

M-85 FFVs were widely deployed in the 1990s (see next subsection). Although no longer commercially offered in America, M-85 FFVs were harbingers for E-85 FFVs, which are widely sold today by LDV manufacturers. More than eight million E-85 FFVs are currently operated on U.S. roadways, although the actual use of E-85 in North America today remains very minimal compared to gasoline.[45] Nearly 100% of the E-85 FFVs on America's roads today were built at the factory by manufacturers such as Ford and General Motors. The vast majority of the other 200+ million LDVs on the road today are equipped with conventional gasoline fuel systems.

This section assesses conversion strategies with potential to enable large numbers of America's in-use LDVs to routinely use ethanol and/or methanol blends. A specific focus is to evaluate feasibility of the following two related strategies to reduce petroleum usage in America's in-use fleet of late-model LDVs:

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[42] U.S. DOE "Vehicle Conversions," National Renewable Energy Laboratory, accessed on Alternative Fuels Database Center website, http://www.afdc.energy.gov/afdc/vehicles/conversions.html.

[43] Ibid.

[44] According to a recently presented paper, "commercial E85 is often not configured with 85% ethanol; US limits are 51-83% by volume," and ethanol concentration typically may only comprise 70% to 77%. (Source: "Evolution of alcohol fuel blends towards sustainable transport energy economy," white paper jointly prepared for the Massachusetts Institute of Technology by Lotus Engineering, BioMCN, Methanex Corporation, Methanol Institute, and SAAB Automobile Powertrain AB.)

[45] The Energy Information Administration estimates that about 40 million gallons of E-85 were dispensed in the U.S. in 2011, or about 0.03% of the gasoline dispensed.

1. Conversion (if not already equipped) of *existing* E-85 FFVs for the capability to additionally use M-85 or lower methanol-gasoline blends
2. Conversion of *conventional* LDVs into FFVs with capability to use gasoline-ethanol-methanol blends

Some knowledgeable individuals believe that today's late-model conventional LDVs are being routinely equipped at the factory to successfully operate on high-level alcohol blends. Many anecdotes can be found about mechanics and engineers operating non-FFVs on E-85 or methanol-gasoline blends up to M-20, with little or no deleterious effects. In cases where materials compatibility upgrades are needed, it has been reported that they can be done with relative ease using "garage mechanic" expertise.[46] Regardless of whether such accounts are accurate, it's important to look beyond the *technical* feasibility of fuel switching in-use LDVs, to also assess the complex associated legal, safety and warranty issues.

Important Note: This report considers only the vehicle-side opportunities and challenges associated with the above-noted strategies. Clearly, their feasibility also depends on the ability of fuel providers to sell ethanol and/or methanol on a commercial scale at established gasoline stations throughout America.

3.2 Regulatory Oversight and Certification Processes

Federal (EPA) as well as California (CARB) regulations prohibit the conversion of an emissions-certified gasoline-fueled LDV to operate on an alternative fuel such as ethanol or methanol unless the conversion system has been evaluated and certified. The process to achieve certification of alternative fuel conversion systems is much more complex and costly than the process to legally sell fuel economy retrofit devices (described above in Section 2). The complexity and costs of the certification processes as a function of oversight by EPA and CARB are briefly described in the subsection below. Greater detail is provided in Section 4.

Certification of an alternative fuel conversion system must be sought by its manufacturer, who must demonstrate compliance with emissions, warranty, and durability requirements of EPA and/or CARB. Because CARB's process is more stringent than EPA's (see below), it appears that EPA can accept CARB certifications, but the reverse is not true:

> *"Manufacturers selling conversion systems for use in California must meet CARB requirements and obtain approval from CARB. EPA Certificates or tampering exemptions are not required, nor will they take the place of CARB certification."* [47]

The manufacturer is defined as a person or entity that manufactures or assembles an alternative fuel retrofit system for sale. Individuals or organizations who wish to convert vehicles to alternative fuels – even for personal use – must use certified conversion systems to avoid violating anti-tampering requirements. For certification purposes (new or conversion), vehicles are categorized in test groups for exhaust emissions (engine families) and evaporative emissions

[46] For example, see the white paper by J. Brackett entitled "Freeing America's Automotive Fleet," September 24, 2012 (copy supplied to TIAX by the Fuel Freedom Foundation).

[47] Ibid.

(evaporative families). Within each family, the vehicles share similar designs and are expected to have similar emission characteristics. Pertinent certification information that affects grouping includes vehicle model, model year, engine and evaporative families, vehicle category, emission standard category, engine displacements, operating fuel, and emission control systems.

Manufacturers wishing to sell and install their alternative fuel conversion systems in California (or a jurisdiction that has adopted California emissions requirements) must first obtain certification from CARB. As noted, CARB's requirements for aftermarket fuel converters are different and more stringent than EPA's requirements.[48] A key difference was codified in 2011 when EPA changed its requirements to better accommodate "age-based" differences among alternative fuel conversions systems. California's requirements, which have remained the same since being adopted in 1995[49], apply to all vehicles regardless of their age. Other key differences – and their implications – between the EPA and CARB certification processes for alternative fuel conversions are detailed in Section 4.

3.3 Ethanol and Methanol Blends as Transportation Fuels

3.3.1 Methanol

3.3.1.1 Overview as a Transportation Fuel

Methanol (CH_30H) is a single-carbon alcohol fuel that works well in spark-ignited internal combustion engines, either in its "neat" (100%) form or when blended with other liquid fuels (gasoline and ethanol). Methanol has a number of beneficial characteristics that make it an excellent alternative fuel for LDVs. There are also challenges, such as methanol's relatively low energy density and its higher corrosivity compared to gasoline. A broad overview is provided below. Vehicle modifications to use methanol in LDVs are discussed in a subsequent section.

Feedstock and Production - Methanol can be made from a wide array of abundant feedstock, making it a very flexible chemical commodity and energy source. The most simple and widely practiced process to make methanol is to use steam reforming of natural gas to make synthesis gas, which is the basic feedstock. Because the U.S. has large resources of inexpensive natural gas to make synthesis gas, methanol can be made in large quantities as a low-cost transportation fuel.

Renewable Sources - Today methanol is mostly made from conventional natural gas; however, increasing volumes are being made from sustainable resources such as biomass and other renewable feedstock. For example, in Iceland one company utilizes CO_2 flue gas and electricity from a geothermal power plant to make renewable methanol for vehicles and trucks. In the Netherlands, another company converts crude glycerin (a residue from processing vegetables and animal fats) into "bio-methanol."

Combustion Characteristics and Emissions – Methanol has advantageous combustion characteristics that make it a very good alternative to gasoline for light-duty vehicles. Neat methanol has a 112 pump octane rating, which is about 27% higher than the octane of regular

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[48] These differences are clarified in an EPA guidance letter CISD-10-24 (Q&A # 9).

[49] Notably, CARB staff just recently began exploring ways to change the California process for certifying alternative fuel conversions.

gasoline.[50] This enables design of spark-ignited methanol engines with higher compression ratios than comparable gasoline engines, providing increased engine efficiency and fuel economy per unit of energy consumed. Methanol also combusts at a lower temperature than gasoline, and therefore can result in reduced NOx emissions compared to gasoline combusted at the same compression ratio. Hydrocarbon emissions from methanol engines are less reactive towards ozone formation and less toxic than complex gasoline hydrocarbons (e.g., aromatics such as benzene, toluene, and xylene). The lower carbon content of methanol, and the lower overall energy needed to produced and distribute it, can result in lower greenhouse gas emissions than gasoline or diesel fuel.

One concern about methanol-fueled LDVs has been the potential for increased emissions of formaldehyde (a lung irritant and carcinogen) compared to conventionally fueled LDVs. EPA and CARB have promulgated stringent formaldehyde emissions standards on LDVs capable of using methanol (and other fuels). This issue is well studied and understood; formaldehyde emissions from methanol-fueled LDVs can be reduced well below the EPA and CARB and standards using catalytic converter technology.[51]

NOTE: Full fuel-cycle emissions analysis is necessary to fully compare air emissions (criteria pollutants, air toxics, and greenhouse gases) from different vehicle types (fuel / technology combinations)**.** This type of analysis takes into account emissions from "upstream processes" (e.g., energy extraction, fuel production and refinement, fuel distribution), and end use (conversion of energy to motive power by the vehicle).

As follow-on work, TIAX is performing a full fuel-cycle emissions analysis on various fuels and vehicle technologies that are discussed in this report.

Liquid Fuel – Methanol is a liquid fuel at ambient temperature and pressure. It is distributed, stored, refilled, and combusted much like gasoline. It is miscible with water, gasoline, ethanol and many organic compounds. As such, it can be integrated with relative ease into the existing fueling infrastructure and LDV technology, although certain issues such as materials compatibility must be addressed (discussed in a subsequent section).

Blending Capability – Methanol can easily be blended with gasoline and ethanol to make a relatively low-cost alternative to gasoline-ethanol blends (E-85) for FFVs (see Section 3.3.3).

Toxicity and Spill Impacts – Being miscible in water, methanol degrades faster than gasoline or diesel, making spills easier to clean up. Like gasoline[52], methanol is toxic to humans. When

[50] U.S. DOE, Fuel Properties Comparison Chart, accessed online at http://www.afdc.energy.gov/progs/fuel_compare.php. Pump octane number number is the average of the research and motor octane numbers.

[51] California Air Resources Board, "Formaldehyde Emissions Control for Methanol-Fueled Vehicles," Research Note No. 97-6, May 1997, accessed online at http://www.arb.ca.gov/research/resnotes/notes/97-6.htm.

[52] According to its Materials Safety Data Sheet (MSDS No. 9950), gasoline is "harmful or fatal if swallowed . . harmful if absorbed through the skin . . . effects the central nervous system . . . and long-term exposure may cause effects" to a variety of specific human organs. Gasoline "contains benzene, a regulated human carcinogen."

spilled in fresh or salt water, methanol "may have serious effects on aquatic life,"[53] although it appears to be significantly less toxic to marine life than gasoline.[54]

Energy Content – The energy content (lower heating value) of neat (100%) methanol is approximately 57,250 Btu/gal; this is about one half as much energy by volume as gasoline (116,090 Btu/gal). When 15% gasoline is blended into neat methanol to make M-85, the resulting "fuel methanol" contains approximately 62% of gasoline's energy content by volume. M-60 contains about 70% of gasoline's energy content by volume.

3.3.1.2 M-85 Use in FFVs

Based on its many beneficial characteristics as a transportation fuel, in the late 1980s California sponsored the simultaneous "rollout" of fuel methanol (M-85) stations and M-85 FFVs. The objective was twofold: 1) to improve air quality, and 2) to displace petroleum. At the peak of this program, approximately 100 public M-85 stations operated in California; more than 12 million gallons of methanol were sold to serve thousands of M-85 FFVs. However, the program ended in the 1990s, in part because the automobile and oil industries were able to improve the emissions performance of conventional LDVs through reformulated gasoline and more-advanced emissions control technologies.

Notably, the California experience with M-85 in the 1980s and 1990s provided a valuable knowledge base for using alcohol fuels. FFVs capable of running on gasoline and methanol were commercialized, fueling stations were built, and this was done on a scale rather than trial basis. Moreover, the M-85 FFV experience served as a solid "learning curve" for LDV OEMs to market E-85 FFVs (see next subsection).

Today, methanol is widely used as a chemical commodity, but its direct use as a motor vehicle fuel in North America is primarily limited to high-performance race cars. For on-road vehicles, methanol's only fuel role is as a component to make biodiesel, where it is used as a reagent to form methyl esters. Methanol is banned as a fuel blend stock in California.[55] EPA permits methanol use (in some states) at concentrations up to 2.75%, when accompanied by 2.75% co-solvent to facilitate miscibility. However, given the Renewable Fuel Standard (RFS) in the U.S., which supports ethanol blending in the U.S. gasoline pool, there is effectively no methanol blended into gasoline today. In part, this is due to issues with methanol–gasoline blends (detailed in this report) as well as strong support in the U.S. for support of corn-based ethanol production.

The primary technical challenge for wide scale use of blends of methanol in FFVs relates to its high corrosivity, which can harm vehicle components that come into contact with the fuel (metals and elastomers) unless they are made methanol compatible.[56] A marketing challenge relates to methanol's lower energy density as compared to gasoline, which reduces vehicle range

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[53] Material Safety Data Sheet for methanol, provided by Methanex Corporation, accessed online at http://www.methanol.org/Environment/Resources/Environment/MX-Methanol-MSDS-US-English-FINAL-Sept08.aspx.

[54] Malcolm Pirnie, Inc., "Evaluation of the Fate and Transport of Methanol in the Environment," Prepared for the American Methanol Institute, January 1999.

[55] "The California Reformulated Gasoline Regulations". California Air Resources Board, Title 13, California Code of Regulations, Sections 2250-2273.5.

[56] Greg Dolan, Methanol Institute, "Methanol Transportation Fuels: A Look Back and Forward," presentation at the International Sympsia on Alcohol Fuels, September 27, 2005. Accessed online at http://www.eri.ucr.edu/ISAFXVCD/ISAFXVPP/MTFLBLF.pdf.

relative to gasoline. However, these issues are well documented and widely understood; they are not considered to be significant barriers to future use of fuel methanol.[57]

3.3.2 Ethanol

3.3.2.1 Overview as a Transportation Fuel

Ethanol (CH_3CH_2OH) is another high-octane alcohol fuel that works well in spark-ignited internal combustion engines, either when blended with gasoline or in its "neat" (100%) form. Like methanol, ethanol has potential to provide numerous societal benefits when used as a light-duty vehicle fuel. These include petroleum displacement and reduced emissions of greenhouse gases, criteria pollutants, and air toxics. Like all fuels, there are also drawbacks and challenges associated with using ethanol as a mainstream fuel for LDVs. Broad discussion of these benefits, advantages and issues is provided below.

Feedstock and Production – Ethanol can be made by distilling and fermenting fruits and seeds from a large variety of plant matter; this includes corn, sorghum, barley, rice, sugar cane, and sugar beets. More than 90% of the ethanol produced in the U.S. is made from corn. Currently there are more than 100 grain ethanol facilities in the U.S., with the collective capacity to produce billions of neat ethanol gallons. In 2011, about 13 billion gallons of ethanol were added to gasoline consumed in the United States. [58]

In other parts of the world, sugar cane and sugar beets are the most common ingredients used to make ethanol. Brazil -- the world's fifth largest country -- has become the largest ethanol producing nation; most Brazilian ethanol is produced by fermenting sugar cane. Brazilians use this ethanol to displace gasoline usage in the large national fleet of ethanol-ready LDVs.

Renewable Sources – Ethanol can also be made by breaking down woody fibers found in trees and grasses. This "cellulosic" ethanol requires a more-complicated process than making conventional ethanol from starchy crops such as corn. However, it is considered a more sustainable renewable energy pathway, and helps address concerns that ethanol production from crops such as corn competes with food production.[59]

Combustion Characteristics and Emissions – Like methanol, ethanol is a high octane fuel that can be blended with gasoline. It has a pump octane number of 110; when blended with 15% gasoline the resulting E-85 has a 105 octane rating.[60] Numerous studies have shown that emissions levels from compatible LDVs can be reduced when using E-85 instead of the baseline gasoline fuel. For example, an emissions testing program at Chrysler found that a 2006 minivan had "substantially lower tailpipe emissions" for reactive hydrocarbons, CO and NOx when it was tested on various gasoline-ethanol blends (E-0, E-10, E-20, and E-85); these emissions were

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[57] TIAX LLC, "Methanol Fuel Blending Characterization and Materials Compatibility: Final Report," for the Methanol Institute, August 27, 2010.

[58] U.S. Energy Information Administration, "Ethanol Made from Corn and Corn Crops," accessed online at http://www.eia.gov/energyexplained/index.cfm?page=biofuel_ethanol_home

[59] U.S. Energy Information Administration, "Ethanol Made from Corn and Corn Crops," accessed online at http://www.eia.gov/energyexplained/index.cfm?page=biofuel_ethanol_home

[60] 60 U.S. DOE, Fuel Properties Comparison Chart, accessed online at http://www.afdc.energy.gov/progs/fuel_compare.php. Pump octane number number is the average of the research and motor octane numbers.

progressively lower as a function of increasing ethanol content. Conversely, emissions of carbonyls (primarily acetaldehyde) increased as a function of the test fuel's ethanol content, peaking with E-85.[61]

In general, hydrocarbon emissions from ethanol fuels are less reactive than those from gasoline, and also have lower toxicity. Greenhouse gas emissions have the potential to be lower with ethanol use, although complex tradeoffs exist and must be managed.[62] As with all vehicle-fuel technologies, it requires "full fuel-cycle analysis" (FFCA) to comprehensively compare and understand the air quality impacts of LDVs when burning E-85 versus gasoline, which typically contains up to 10% ethanol. The FFCA process goes beyond direct-vehicle emissions to account for "upstream" emissions associated with fuel production, preparation, and transportation (refer back to the note in Section 3.3.1.1).

Liquid Fuel – Like methanol, ethanol is fully miscible with gasoline and water. Ethanol is already distributed at scale throughout the U.S. as a blending and oxygenation agent for gasoline. In Brazil and other countries, it is widely used as a neat or near-neat alcohol fuel that has been fully integrated into liquid petroleum fuel infrastructures.

Blending Capability – Ethanol is blended into gasoline at various levels throughout the U.S. gasoline distribution system. E-10 is a low-level blend classified by EPA to be "substantially similar" to gasoline for use in any gasoline-powered vehicle; according to the U.S. DOE, more than 90% of U.S. gasoline consists of low-level ethanol blends (E-10 or lower) to boost octane, meet air quality requirements, or satisfy the federal Renewable Fuel Standard. Although not yet sold at the pump, blends up to 15% ethanol (E-15) have recently been approved by EPA for use in vehicles that are 2001 model year and newer. E-85 (fuel ethanol) is a high-level blend "containing 51% to 83% ethanol" that is intended to be used exclusively in FFVs; this fuel cannot legally be used in conventional gasoline-powered vehicles.[63] Blending gasoline into the ethanol helps automakers address certain vehicle needs (e.g., cold starting). It also helps gasoline fuel suppliers to meet current standards for reduced benzene content.

Toxicity and Spill Impacts – Ethanol is ingested by humans in alcohol drinks such as beer and distilled spirits; in normal use it is rated more as an irritant or "slightly hazardous" in cases of skin contact or ingestion.[64] Like methanol, ethanol spills into fresh or salt water are more manageable than petroleum fuels and less harmful to marine life, largely due to its miscibility with water.

Energy Content – The energy content (lower heating value) of neat (100%) ethanol is approximately 76,330 Btu/gal; this is about two thirds as much energy by volume as gasoline

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[61] Mahmoud K. Yassine and Morgan La Pan, Chyrsler Group LLC, "Impact of Ethanol Fuels on Regulated Tailpipe Emissions," Society of Automotive Engineers paper No. 2012-01-0872, 4/16/12.

[62] Reduced GHG emissions at the tailpipe must be weighed against potential land-use decisions affecting GHG emissions, especially regarding acreage dedicated to conventional ethanol production. For example, converting non-crop lands to corn production would increase GHG emissions, since the non-crop GHG storage is eliminated. For corn-produced ethanol this has been offset partially by higher corn yields per acre. Cellulosic ethanol can provide the best overall reduction in GHG emissions, although low-cost production technologies have not yet been commercialized.

[63] U.S. DOE, National Renewable Energy Laboratory, Alternative Fuels Data Center, "Ethanol Blends", accessed online at http://www.afdc.energy.gov/fuels/ethanol_blends.html.

[64] "Material Safety Data Sheet: Ethanol, Absolute," VEE GEE Scientific, accessed online at http://www.cen.iitb.ac.in/cen/msds/ethanol.pdf

(116,090 Btu/gal). When 15% gasoline is mixed in to make E-85, this blend contains approximately 77% of gasoline's energy content by volume. This means that is takes more E-85 stored onboard an LDV to equal the same energy as a given volume of gasoline. Notably, E-85 sold in the U.S. often actually contains anywhere from 17% to 49% gasoline (83% to 51% ethanol); these blends have proportionally higher volumetric energy density than E-85.[65]

3.3.2.2 E-85 Use in FFVs

As noted, approximately eight million E-85 FFVs are already on the road in North America today. A number of automakers (e.g., Chrysler, Ford, General Motors, Mercedes Benz, Mitsubishi, Nissan, and Toyota) are producing 2012 model E-85 FFVs. Most of the models offered are light-duty pickup trucks and SUVs. Notably, automakers have been highly motivated to produce these FFVs as a strategy to comply with Federal Corporate Average Fuel Economy (CAFE) standards. There are approximately 48 public E-85 stations in California, and more than two thousand are located nationally (the greatest station density occurs in "corn belt" states such as Illinois and Minnesota).[66] Still, nearly 100% of America's fuel usage in the LDV sector comes from gasoline (typically G-90 / E-10).[67]

Like M-85, using E-85 in FFVs entails technical and marketing challenges. These include materials compatibility issues, lower energy density compared to gasoline, and relative fuel price. The certification and sale of approximately eight million in-use FFVs in America is indicative that technical issues have been successfully addressed. Fuel price may be a barrier that helps explain why the actual volume of E-85 being used in America's FFV fleet is minimal. Although prices vary by location and other factors, E-85 often costs more on an energy-equivalent basis than gasoline.[68,69]

3.3.3 Potential for Gasoline–Ethanol–Methanol Blends

Increased interest has recently been expressed about the potential for blends of gasoline, ethanol and methanol (so-called "GEM" fuels) to be used in FFVs. GEM blends can be configured to have the same target stoichiometric air-fuel ratios as E-85; a blend of 60% methanol with 40% gasoline (M-60) has the same energy content as E-85. This means that fuel injectors equipped on today's E-85 FFVs will work with M-60 (i.e., larger injectors would NOT be required to compensate for the lower energy density of methanol compared to ethanol). Representatives from the automotive and fuel industries have noted that FFVs operating on GEM blends could offer performance, logistical and cost advantages if used in America's large fleet of in-use FFVs. Specifically,

> *"Introduction of methanol (which can be made extremely simply and cheaply from*

[65] Ibid.

[66] U.S. DOE, National Renewable Energy Laboratory, Alternative Fuels Data Center, accessed online at http://www.afdc.energy.gov/afdc/locator/stations/state.

[67] The Energy Information Administration estimates that about 40 million gallons of E-85 were dispensed in the U.S. in 2011, or about 0.03% of the gasoline dispensed.

[68] "E85: Will it Save You Money?", by Joe Wiesenfelder, Cars.com, August 31, 2012, accessed online on http://www.cars.com/go/advice/Story.jsp?section=fuel&subject=fuelAlt&story=e85.

[69] U.S. DOE, National Renewable Energy Laboratory, Alternative Fuels Data Center, "Ethanol Blends", accessed online at http://www.afdc.energy.gov/fuels/ethanol_blends.html.

natural gas) into gasoline-ethanol mixtures, can be used to create drop-in fuels equivalent to E85 and can bring the price of an alcohol-based fuel for spark-ignition engines down to less than that of gasoline (on a per-unit-energy basis, before tax is applied)." [70]

With approximately eight million in-use FFVs already designed to use E-85, low-cost GEM blends have potential to significantly improve petroleum displacement in America's LDV fleet. On the vehicle side, the main technical issue involves methanol's greater corrosivity. Depending on the extent that fuel systems of modern E-85 FFVs are also compatible with methanol (M-60 or lower), the lower fuel costs of GEM blends could incentivize greatly reduced gasoline usage in millions of deployed FFVs. Also, a significant percentage of America's existing conventional gasoline LDVs (non-FFVs) *may be* compatible with GEM blends. It's conceivable in today's global markets that OEMs are producing only GEM-ready LDVs, since doing so might reduce overall costs by condensing product lines, vehicle platforms, fuel system components, etc.

However, the extent to which each OEM's late-model LDV platforms are GEM fuel ready is unknown; such information is likely to be proprietary. Independently, some parties have attempted to demonstrate that "ordinary American cars" can readily be converted to operate on methanol and GEM fuels, with minimal vehicle changes, low costs and clear societal benefits.[71]

To advance this concept as a potential national strategy for reducing petroleum usage, further investigation and testing would be needed, ideally with strong government and industry involvement. Such testing would need to investigate the effects of various GEM blends on FFVs and non-FFVs under controlled laboratory conditions, for all critical issues (e.g., materials compatibility, durability, warranty, safety, anti-tampering and emissions requirements), according to applicable testing protocols and standards for LDVs undergoing fuel conversion (e.g. EPA, CARB). To define the universe and boundaries for the program, an assessment would be needed of which LDV makes, models and model years are equipped for GEM blend compatibly; this would ideally include evaluations about remaining vehicle life and payback on investments. Thorough testing would be needed to ensure that all materials coming into contact with fuel would be able to withstand the worst-case for corrosiveness.

Notably, it may take new thinking and metrics to interpret the implications of such testing, should it occur. For example, suppose GEM fuel blends are definitively shown to be feasible for in-use LDVs and provide significant cost-effective societal benefits, but they marginally accelerate fuel system component failures due to greater fuel corrosivity? Such tradeoffs would need to be carefully documented, understood and weighed.

3.4 Aftermarket Systems to Convert LDVs for Flex-Fuel Capability

The following subsections focus on E-85 FFVs because they represent the current market in North America for FFV technology. The same basic discussions that follow also apply to M-85

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[70] J.W.G. Turner and R.J. Pearson, Lotus Engineering, E. Dekker, BioMCN, B. Iosefa, Methanex Corporation, G.A. Dolan, Methanol Institute, K. Johansson and K. ac Bergstrom, SAAB Automobile Powertrain AB, "Evolution of alcohol fuel blends towards sustainable transport energy economy," white paper jointly prepared for the Massachusetts Institute of Technology, April 2012.

[71] For example, see "Methanol Wins" by Robert Zubrin, December 1 2011, National Review Online. Zubrin claims to have operated a non-FFV 2007 Chevy Cobalt on M-100 after making minimal hardware and software changes, advancing spark timing to take advantage of methanol's higher octane rating. He claims lower emissions and higher fuel economy were corroborated during emissions testing. However, essential details (test procedures, test apparatus, driving schedules, etc.) were not provided.

FFVs; significant differences involve 1) the lower energy content of M-85 relative to E-85; and 2) the greater materials compatibility challenges presented by methanol versus ethanol. M-85 FFV technology and methanol (including M-60 used in GEM blends) are specifically discussed when there are important implications to aftermarket FFV conversion kits. "Neat" alcohol fuels (M-100 and E-100) are only briefly discussed; currently, both lack viability in America as alternative fuels for on-road LDVs.[72]

3.4.1 Basic Operational Principle for Aftermarket FFV Conversion Devices

Figure 2 shows the changes (cited by the U.S. government) that are needed for a modern conventional gasoline LDV to be converted into an E-85 FFV; these apply for FFVs converted at the factory by an OEM[73], but similar changes reportedly apply for aftermarket conversions.[74] According to these sources, the modifications that are currently needed for FFV conversions are not trivial; many different hardware components are needed, and special fuel system materials are needed to durably withstand ethanol's higher corrosivity compared to gasoline.

Still, as described in Section 3.3.3, today there appears to be growing component commonality between non-FFV and FFV LDV platforms sold in America. For example, a special alcohol sensor is no longer needed to enable an FFV's ECU to control fuel injection rate according to the energy content of the operable fuel blend. Instead, the sophisticated sensors and engine electronics of modern gasoline LDVs are capable of instantaneously detecting fuel composition and compensating for the necessary volume of fuel. In the FFV diagram, this is collectively referred to as a "fuel identifier system." Note that the fuel injection system must still be designed for greater fuel flow, to account for the lower energy content of higher ethanol blends compared to gasoline (E-10).

[72] Gasoline is blended into neat alcohol fuels to make E-85 or M-85 for multiple reasons. These include: to add flame luminosity, improve lubricity, and facilitate engine cold starting.

[73] Renewable Energy Laboratory, Alternative Fuels Data Center, http://www.afdc.energy.gov/afdc/vehicles/flexible_fuel.html?0/E85/.

[74] Also see DOE's section and video that describe (according to GM) each component that needs to be modified to convert an existing conventional LDV into an E-85 FFV (http://www.afdc.energy.gov/vehicles/flexible_fuel_video_transcript.html).

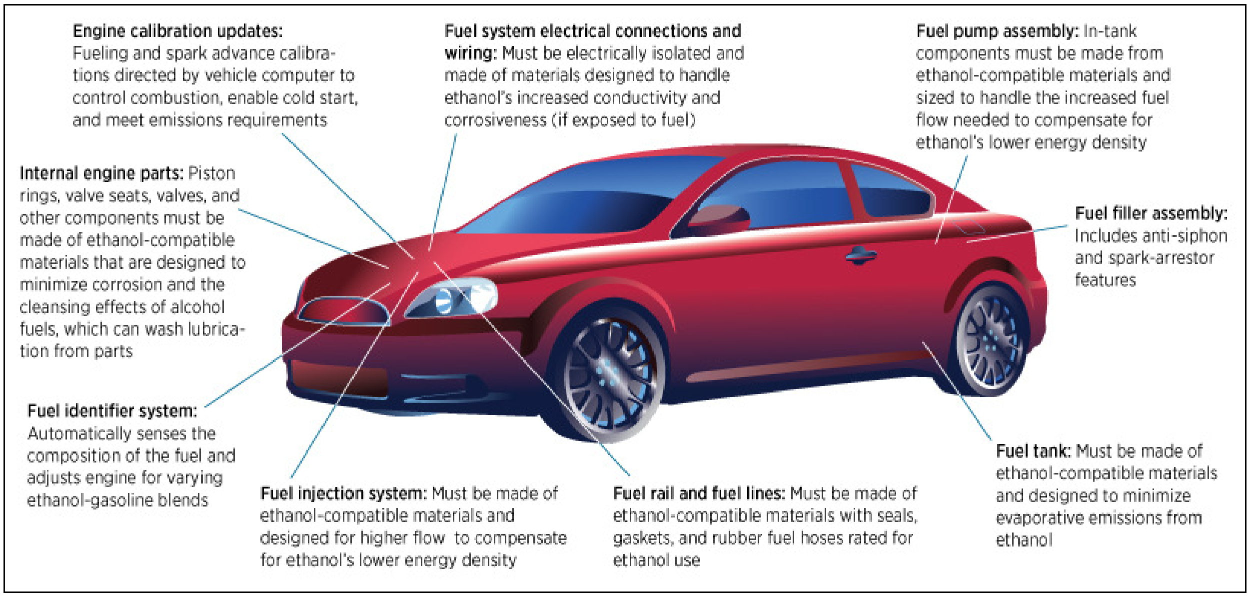

Figure 2. Special components of an E-85 FFV compared to conventional gasoline LDV (Source: U.S. DOE, http://www.afdc.energy.gov/vehicles/flexible_fuel.html.)

Clearly, specialized parts and components are needed to convert a conventional LDV into an FFV and properly operate it on varying blends of E-85 and gasoline (E-10). A commonly cited estimate is that it costs OEMs about $100 per vehicle to convert LDVs at the factory into FFVs. However, it's conceivable that these specialized components are becoming the "new normal" across multi-national car platforms. OEMs may be doing this to cost-effectively meet the needs of many regions where different liquid fuels are available at the pump.

If the above is accurate, it can be reasonably concluded that 1) the incremental cost of manufacturing alcohol-ready LDVs is approaching zero and/or becoming inconsequential; and 2) there are many more alcohol-ready LDVs in the existing U.S. fleet beyond the known FFV population of about eight million. This means that potentially, through an LDV retrofit strategy with relatively modest vehicle changes, many millions of in-use LDVs in America's fleets could use high-level alcohol blends. This could open up demand for relatively low-cost, high-octane GEM blends (e.g., up to M-60) that could offer performance advantages and a compelling payback for end users.

While major challenges are associated with such a strategy, the potential societal benefits are very large. Key questions include: To what extent are modern LDV components compatible and durable with the worst-case fuel for corrosivity (methanol)? What would be needed to ensure EPA or CARB to exempt such systems from anti-tampering requirements? How much testing would be needed to prove that OEM emissions-control and fuel-system components would not be subjected to unacceptable deterioration or durability tradeoffs? What would be the emissions and air quality impacts, on a full fuel-cycle basis?

The next subsection discusses the case of a specific product on the market today that converts late model conventional gasoline LDVs to operate as E-85 FFVs.

3.4.2 Example Aftermarket Fuel Conversion Device

This report takes a closer look at the Flex-Box Smart Kit™, which is the only aftermarket FFV conversion device certified and approved by EPA.[75] The Flex-Box Smart Kit™ is developed and marketed by Flex Fuel US (Chicago, IL). This device allows compatible LDVs to operate on any combination of E-85 and gasoline (typically G-90 / E-10). According to the manufacturer, the Flex Box system is currently marketed in North America only for its use with ethanol-gasoline blends. A wide array of Ford and Chrysler LDV types are compatible for conversion to use E-85 via the Flex Box; the latest model year that could be corroborated was 2007 (based on the Flex Fuel US website, accessed 4/30/12). The manufacturer notes that the system is "easy to install"; the time and cost to install the system is discussed in a subsequent section.

It is important to note that this aftermarket device has not been certified by CARB. According to Flex Fuel U.S.'s spokesman and CEO, CARB's requirements to flag error codes under the on-board diagnostics (OBD II) compliance demonstration presented problems. He stated that:

> "*We explained that you would get a check engine light if our system failed (because you would not get the correct fuel/air mixture on E85 with our system down), and if we changed the OBD II system we would lose warranty on the vehicle. I think we could have negotiated this requirement out of the approval process, but we have focused our efforts in the Midwest where CARB cert isn't necessary*".[76]

This statement provides a good example regarding the implications of differing certification procedures for EPA and CARB (see Section 4).

The remainder of Section 3 provides additional discussion about systems that convert conventional LDVs into FFVs. Specific context about aftermarket systems is provided through reference to the Flex-Box Smart Kit™ device. Discussion about OEM FFV technology is provided to help better define and understand aftermarket FFV conversion systems.

3.5 Issues with Developing / Marketing Aftermarket Flexible Fuel Systems

3.5.1 Vehicle Manufacturer Warranty

As previously described, a somewhat gray area for customers and end users is whether or not installing an aftermarket device will void the original vehicle manufacturer's warranty. Often, claims by manufacturers can be more simplistic than reality. For example, the Flex Fuel US website states that "since Flex-Box Smart Kit™ is EPA-certified, your vehicle's warranty isn't affected."[77] To further understand the potential impacts of installing the Smart Box on late-model Ford LDVs, TIAX contacted Ford Dealerships in Chicago (US Flex Fuel's main location) and reviewed Ford literature. New Ford vehicles are covered by several different warranties that include 3 year / 36,000 mile "bumper to bumper" and 5 year / 60,000 mile powertrain coverages. As clearly stated in warranty stipulations from the 2012 Ford F-150 Owner's Manual (see Table

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[75] Spreadsheet available at EPA's website: http://www.epa.gov/otaq/consumer/fuels/altfuels/altfuels.htm#4

[76] Personal communication to TIAX staff from Don Althoff, Flex Box CEO.

[77] Flex Fuel US website, http://www.flexfuelus.com/index.html, accessed April 30, 2012.

3), any damage to the new vehicle caused by alterations or modifications will not be covered. However, these warranty stipulations do not state that merely installing aftermarket devices will void the warranty.

Table 3. Ford 2012 F-150 Warranty Stipulations[78]

Damage Caused by Alteration or Modification
The **New Vehicle Limited Warranty** does not cover any damage caused by:
• Alterations or modifications of the vehicle, including the body, chassis, or components, after the vehicle leaves the control of Ford Motor Company • Tampering with the vehicle, tampering with the emissions systems or with the other parts that affect these systems (for example, but not limited to exhaust and intake systems) • The installation or use of a non-Ford Motor Company part (other than a certified emissions part) or any part (Ford or non-Ford) designed for off-road use only installed after the vehicle leaves the control of Ford Motor Company, if the installed part fails or causes a Ford part to fail. Examples include, but are not limited to lift kits, oversized tires, roll bars, cellular phones, alarm systems, automatic starting systems and performance-enhancing powertrain components or software and performance "chips."

When contacted, Ford dealership representatives corroborated the warranty-related claim made by Fuel Flex US. The Ford dealers stated that it is against federal law for any OEM to explicitly void the warranty of a vehicle if an EPA-approved aftermarket device approved is installed.

EPA regulations governing emissions control system performance warranties and aftermarket parts state that:

> "*No valid emission performance warranty claim shall be denied on the basis of the use of a properly installed certified aftermarket part in the maintenance or repair of a vehicle…*
>
> "*Except as provided in §85.2104(h), a vehicle manufacturer may deny an emission performance warranty claim on the basis of an uncertified aftermarket part used in the maintenance or repair of a vehicle if the vehicle manufacturer can demonstrate that the vehicle's failure to meet emission standards was caused by use of the uncertified part*."[79]

TIAX reviewed owner's manuals from two major OEMs to assess the effects on a vehicle's warranty if malmaintenance occurs or if the vehicle is mis-fueled. The 2012 Ford F-150 Owner's Manual states the following:

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78 Ford Motor Company, "Ford 2012 Model Year Warranty Guide", accessed on line on April 23, 2012 at: http://www.motorcraftservice.com/pubs/content/~WOCF12/~MUS~LEN/41/12frdwa5e.pdf

79 40 C.F.R. 85.2105.

"*If your vehicle is flex-fuel capable, it is designed to use Fuel Ethanol, 'Regular' unleaded gasoline or any mixture of the two fuels. Use of other fuels such as Fuel Methanol may cause power-train damage, a loss of vehicle performance, and your warranty may be invalidated.*"

The 2012 Chrysler Group Charger Owner's Manual states the following for the flex fuel vehicles:

"*Your vehicle will operate on both unleaded gasoline with an octane rating of 87, or E-85 fuel, or any mixture of these two.*"

For non FFVs, the warning about improper fuel use is more explicit:

"*DO NOT use gasoline containing methanol or gasoline containing more than 10% Ethanol. Use of these blends may result in starting and drivability problems, damage critical fuel system components, cause emissions to exceed the applicable standard, and/or cause the "Malfunction Indicator Light" to illuminate.*" [80]

Another concern of customers and end users is which party is held liable for the emissions warranty when a part of the system fails on a converted vehicle. In the 2006 Updated Certification Guidance for Alternative Fuel Converters, the EPA states:

"*The vehicle's original manufacturer remains liable for warranty of any systems which retain their original purpose following conversion, except in cases where the failure of such a system is determined to be caused by the conversion. If the failure of such a part or system could be traced to the conversion, then the liability would lie with the conversion certifier. For example, a good indication of where the liability lies in such situations would be whether the failure of a part or system is also occurring in non-converted configurations of the same vehicle. The conversion system manufacturers would be responsible for the emissions warranty for any parts or systems added by the conversion.*"[81]

3.5.2 Drivability, Range, and Maintenance

As previously noted, pure ethanol's volumetric energy density is about 71% of pure gasoline's, resulting in reduced fuel economy (but not necessarily fuel efficiency) when E-85 is used in current-technology FFVs. (Methanol's energy density is even lower than ethanol's.) As the percentage of ethanol (or methanol) in an alcohol-gasoline blend increases, the greater the drop in energy density compared to gasoline. Depending on the relative engine efficiencies of the FFV when operated on varying ethanol-gasoline blends, this may reduce vehicle range (distance that can be driven between refueling events) and increase the frequency of refueling.

For example, Table 4 lists EPA's official combined city and highway fuel economy ratings for four different 2012 FFV models fueled by regular gasoline and E-85. As shown, the average drop in miles per gallon when driven on E-85 (specified for these tests at 85% ethanol, 15% gasoline) is about 29%.[82] This reduction in fuel economy is roughly commensurate with the

[80] 2012 Charger Owner's Manual

[81] EPA, "Updated Certification Guidance for Alternative Fuel Converters," 2006

[82] U.S. DOE, http://www.fueleconomy.gov/Feg/bymodel/2012.shtml

reduced energy content of test-grade E-85 (77% by lower heating value) compared to gasoline. EPA gathers this information from official fuel economy testing performed on each certified LDV; road conditions are simulated on a chassis dynamometer in an emissions laboratory.

Table 4. Comparison of EPA combined fuel economy ratings for example FFV models

FFV Information			EPA Combined Fuel Economy (mpg)		%
Model Yr.	**Make**	**FFV Model**	**Gasoline**	**E-85**	**Difference**
2012	Ford	Focus SFE	33	23	-30.3%
2012	Chevy	Malibu	26	18	-30.8%
2012	Saab	9-3 Convertible	25	18	-28.0%
2012	Dodge	Avenger	22	16	-27.3%
			Average % Difference		**-29.1%**

EPA's published fuel economy numbers may sway some interested parties from using E-85 in their FFV, or converting an existing LDV into an FFV. On the other hand, alcohol fuel advocates tend to dismiss government fuel economy ratings as not being representative of real-world FFV operation on E-85. For example, the following comes from a technical paper jointly written by an EPA official and an engine industry expert,

"*Relatively little fuel economy and emissions data has been published for engines operating with fuel blends ranging between 10% and 85% ethanol. Ordinarily, neither dedicated fuel vehicles nor FFVs operate in this range for a significant amount of time, since these "intermediate" fuel blends are not produced commercially in the U.S. Consequently, there has been little work to optimize the engine efficiency over this range, improving it to the level where it would offset the additional fuel cost.*" [83]

Some informed parties indicate that existing FFVs can achieve the same or better fuel economy when operated on E-85, because stock FFV hardware and software are able to partially optimize for ethanol's good combustion characteristics. For example, it's been reported that alcohol fuels may provide additional improvements in engine efficiency and power density due to ethanol's high octane rating and evaporative cooling effect.[84,85] An EPA official has noted that "engine improvements can compensate for as much as 25-30% loss in energy density," and ethanol-fueled engine efficiency can exceed the "best gasoline engines" across many ethanol-gasoline blends. He notes that E-30 provides "high efficiency over a broad range" and this efficiency gain exceeds the fuel's diminished energy density.[86] However, this is in reference to "dedicated fuel vehicles;" it's unknown if such tests were conducted on ethanol vehicles that had greater optimization for ethanol's fuel properties than is typically available for FFV engines.

A final point regarding energy content and vehicle efficiency – which dictate vehicle range and refueling frequency – comes from experience with other types of alternative fuel vehicles.

[83] Matthew Brusstar (U.S. EPA) and Marco Bakenhus (FEV Engine Technology, Inc.), Economical, High-Efficiency Engine Technologies for Alcohol Fuels," technical paper for International Alcohol Fuel Symposium, not dated, accessed online 9/4/12 at http://www.americanenergyindependence.com/alcoholengines.aspx

[84] Moore W., Foster M., Hoyer K., "Engine Efficiency Improvements Enabled by Ethanol Fuel Blends in a GDi VVA Flex Fuel Engine" SAE International. Published on 04/12/2011

[85] Mahmoud K. Yassine and Morgan La Pan, Chyrsler Group LLC, "Impact of Ethanol Fuels on Regulated Tailpipe Emissions," Society of Automotive Engineers paper No. 2012-01-0872, 4/16/12.

[86] Matthew Brusstar, Advanced Technology Division, National Vehicle and Fuel Emissions Laboratory, U.S. EPA, "Sustainable Technology Choices for Alternative Fuels," presented at ISAF XV, September 2005.

Market acceptance has steadily been growing in recent years for CNG and battery-electric LDVs, which provide significantly less range than FFVs operated on E-85. Americans appear to be embracing the idea that gasoline-equivalent range (i.e., 300+ miles) is not needed for typical daily driving needs.

To investigate how end users perceive the attributes of E-85 FFVs obtained through aftermarket conversion kits, TIAX contacted two fleet customers who have used the Flex-Box Smart Kit™ on their vehicles for at least one year (Table 5). The contact information for these users was provided Flex Fuel US LLC.

Table 5. Contacted End Users of Flex Fuel US Flex-Box Smart Kit™

Fleet / End User	# Vehicles Converted	Position of Person Contacted
City of Chicago	25 Crown Victoria police vehicles	Senior Automotive Equipment Analyst
Iowa National Guard- Camp Dodge	50 LDVs (passenger cars, police vehicles, various light trucks)	Head of Fleet Maintenance

Representatives from both fleets / end users were interviewed via telephone. The following summarizes the interviews. It is important to note that 1) the comments that follow come from only two end users of converted E-85 FFVs; 2) results were provided anecdotally without data; and 3) these converted FFVs are being operated in real-world fleet service (which is different than the controlled laboratory testing used to develop and publish fuel economy ratings).

Iowa National Guard -- the Iowa National Guard (ING) paid "about $900 to $1,000" for each FFV conversion kit. ING mechanics performed all installations of the kit on about 50 vehicles, ranging in type from passenger cars to F-350 pickup trucks. The hardest part of the installation process involved working around, and with, the OEM wiring system. It was not necessary to disable anything involving the OEM vehicles during the installation process. The first FFV conversion required "about a half day" to install; subsequently, the installation process has been reduced to about two hours.

ING's overall experience using about 50 converted E-85 FFVs has been very favorable. This converted FFV fleet is normally operated 100% on E-85. Drivability and driver comfort differences have generally been negligible when compared to the pre-conversion vehicles operated on oxygenated gasoline (G-90 / E-10). In the case of Crown Victoria FFVs operated by military police, drivers noted a power improvement on E-85 versus gasoline (E-10). Drivers in the fleet have observed a small ("almost unnoticeable") decrease in fuel economy when running on E-85; notably, the vehicles are only operated for short distances within the compound and military reservation. Under a U.S. DOE contract, IWG pays $1.42 per gallon for E-85 and $3.43 per gallon for oxygenated gasoline. It is not known what the actual ethanol and gasoline percentages are in the E-85 that IWG purchases.

IWG performs routine maintenance on the converted FFVs (oil changes, etc.) every 5,000 miles; there has been no need to perform additional maintenance. In fact, there has been a decrease in maintenance required for the post-conversion Crown Victoria military police vehicles, which are used heavily. Prior to conversion, these vehicles experienced carbon buildup on fuel injectors, which made it necessary to flush the injector system periodically to remove such buildup.

City of Chicago – The City of Chicago converted 25 of its Crown Victoria police cars (2005 and 2006 model years) into E-85 FFVs using the Flex-Box Smart Kit™. (In fact, the City's first converted vehicle was used by Flex Fuel US as the emissions and durability vehicle to achieve EPA certification on the kit.) Including installation (performed by a local Ford dealer), the per-kit cost was "about \$1,800 to \$2,000." These conversions were done before the 2007 model year, when Ford came out with its factory-built Crown Victoria E-85 FFV. Today, all 1,600 of Chicago's OEM Crown Victoria police cars are E-85 FFVs. The City's intent is to operate all its FFVs on E-85; it is believed that this goal is being met.

The converted FFV police cars are operated essentially the same as the OEM FFV police cars. Fuel economy records indicate there is a 10% to 20% drop in fuel economy for the FFVs when operated on E-85 versus oxygenated gasoline (G-90 / E-10). The actual relative percentages of ethanol and gasoline in the city's E-85 fuel are unknown. The police cars are mostly operated in a city-driving duty cycle, with "minimal highway driving". No changes in performance or maintenance have been reported for the converted (or OEM) FFVs relative to the City's experience with gasoline police cars. Beyond police cars, the City intends to further convert its fleet to E-85, if no OEM FFVs are offered. This includes potentially converting hybrid-electric vehicles to operate on E-85. The local Ford dealership is contracted for general maintenance and repairs of the converted FFVs. However, the overall warranty for each converted FFV is provided by Flex Fuel US. The fact that the kits are EPA-certified gave the city essential assurance that the vehicle conversions would not constitute tampering.

3.5.3 Materials Compatibility with Alcohols

No documentation of hard data are available about materials compatibility of FFV conversion kits when regularly using alcohol fuels. Based on anecdotal input from both fleets that have converted 25 or more LDVs to use E-85 blends, components of the Flex-Box Smart Kit™ device have not been adversely affected by ethanol's higher corrosivity.

More is known and documented about the experience of FFV OEM's in this area. Ford has defined a component to be "alcohol fuel compatible" if it performs satisfactorily, is durable, and does not contaminate the fuel when tested in worst-case methanol-gasoline and ethanol-gasoline blends (up to 85% alcohol). As transportation fuels, methanol is significantly more challenging than ethanol for materials compatibility issues. For example, it is more corrosive to aluminum than ethanol. Automakers, therefore, must pay more attention to the wetted fuel system components of methanol vehicles compared to ethanol- and gasoline-fueled vehicles. Also, fuel dispensing materials (e.g., the pump) must be designed to handle the corrosivity of methanol fuels.

Refer back to Section 3.3.2 about the typical fuel system components, hardware and software changes that have been applied to enable conventional LDVs to become E-85 FFVs. Fuel system components that have been modified include the fuel cap, fuel lines, fuel pump, fuel tank, and elastomers such as o-rings. Ford in particular was an early leader with FFV technology and how to ensure compliance with materials compatibility issues. Ford tested all materials that came in contact with the alcohol fuel or fuel vapors. For the M-85 Taurus development, they upgraded fuel lines and rails and used stainless steel or glass filled poly phenylene sulfide resin to provide alcohol compatibility. For elastomers like o-rings, Ford found that high fluorine content fluoroelastomers demonstrated compatibility with alcohol fuels. Materials for fuel pumps, injectors, and fuel sensors were upgraded to ensure durability.

Notably, Ford has indicated that the same special materials and procedures developed for its M-85 FFV were used in its E-85 FFV line. This suggests that today's E-85 FFVs from Ford have been designed for the worst case for materials compatibility: methanol rather than ethanol. However, little hard information exists regarding the extent to which today's late-model FFVs (or non-FFVs) are already compatible for methanol blends. Refer back to Section 2.7.3 about preserving the viability of OEM warranties.

3.5.4 Engine Components and Design

Historically, engine *component* changes for FFVs to accommodate alcohol fuels have included wider bandwidth injectors, higher fuel pump delivery volume, alcohol sensors, and engine-emissions calibration. However, in today's most modern E-85 FFVs, some of these changes are no longer applicable (e.g., a special alcohol sensor is no longer needed). Some argue that it has become less costly and easier for LDV OEMs to build "world car" platforms that meet the same materials compatibility and design requirements across many different fuel types (e.g., neat ethanol in Brazil, high methanol blends in China). In any case, if the American FFV fleet is to routinely use variable blends of GEM fuels (ethanol, methanol, and gasoline), further work is likely to be needed to define and address tradeoffs involving vehicle performance, fuel economy, materials compatibility, emissions performance, on-board diagnostics, warranty, and recall mitigation.

In the past, engine *design* changes have also been necessary to accommodate alcohol fuels. These have included the following:

- Changes to cylinder heads to address pre-ignition of M-85 -- Methanol's low surface ignition temperature and hot spots in the combustion chamber can cause fuel pre ignition (knock).[87] To eliminate pre-ignition, Ford made substantial changes in the cylinder heads and also incorporated a colder heat range spark plug. Because ethanol is much less prone to pre-ignite due to its higher surface ignition temperature, these engine changes may have not been needed for E-85 FFVs.

- Cylinder bore/piston ring wear and valve seat wear -- Methanol requires greater fuel flow in an FFV compared to gasoline, which can lead to "bore washing" from greater friction. Coupled with methanol's solvent nature, this can lead to abrasive bore/piston ring wear. To resolve this, Ford incorporated an improved iron that contained less ferrite and higher Brinell

[87] *Ibid.*

hardness for its FFV engines. Ford also specified other changes to improve ring wear. To address valve wear, Ford found that it was necessary to change exhaust valve seat inserts.

3.5.5 Emissions Control Systems

With today's advanced emissions control technologies, late-model E-85 FFVs do not require a fuel sensor; instead, they can rely on the oxygen sensors in the emissions control system. However, it is unclear if today's "fuel identifier" systems in FFVs will be adequate for FFVs using blends of three different fuels (GEM blends). The ECM will need to identify which fuel is being used and instantaneously switch to the appropriate engine calibrations. Beyond performance considerations, it will be necessary to demonstrate that converted vehicles will continue to meet applicable emissions standards for any combination of methanol, ethanol, and gasoline.

One promising approach is to ensure that the maximum methanol percentage of GEM blends is M-60, which is stoichiometrically equivalent to E-85. Potentially, no major new calibrations or hardware changes will be necessary for the ECM and engine systems associated with fuel and emissions control. However, emissions control systems on late-model LDVs are quite complex and include closely integrated evaporative controls, engine controls, on-board diagnostics, and exhaust aftertreatment systems. This makes it very difficult to estimate the extent to which additional changes would be needed to make existing FFVs capable of operating on GEM blends and achieving compliance with all applicable EPA and/or CARB emissions requirements.

For example, to meet applicable tailpipe emissions standards, current-model E-85 FFVs use closed-loop air-fuel systems and three-way catalytic converters similar to those on conventional gasoline LDVs.[88] In the past, methanol FFV catalysts required more precious metals and were therefore more costly to produce. Notably, Ford's M-85 FFV Taurus was designed to meet California's TLEV standard, whereas Ford's E-85 FFVs that came later were designed to meet federal standards. Apparently for this reason, the methanol FFV included close-coupled, light-off catalysts as well as under-floor catalysts, whereas the ethanol version only included under floor-catalysts[89]. With ongoing advances in catalyst design and early catalyst light-off strategies, it is conceivable that no new catalyst formulations would be required for today's FFVs to achieve equivalent or better emissions performance operating on GEM fuels; possibly, the same would be true for gasoline vehicles operated on GEM fuels.

Another emissions issue involves meeting applicable evaporative emissions requirements. Worst-case for evaporative emissions can result from using lower-level alcohol-gasoline blends (roughly 10% alcohol), which represent peak vapor pressure. This increases fuel evaporation, requiring modifications to the evaporative emissions control system to comply with EPA and CARB requirements. Since newer vehicles re-circulate less fuel than older systems, there is less fuel temperature rise, which helps to lower evaporative emissions. Fuel permeation through hoses, o-rings, and fuel tanks causes additional reactive organic emissions that need to be controlled.

[88] Catalyst formulation may be different for the current ethanol FFVs but cost is believed to be comparable to gasoline catalysts.

[89] Cowart, J.S., W.E. Boruta, J.D. Dalton, F.F. Dona, F.L. Rivard II, R.S. Furby, J.A. Piontkowski, R.E. Seiter, and R.M. Takai, "Powertrain Development of the 1996 Ford Flexible Fuel Taurus," SAE 952751

In general, evaporative emissions from E-85 FFVs are reasonably well controlled with proper material specification. In fact, since all current cars are compatible with E-10 today, and new rules will allow E-15 use in the newest LDVs, it appears that late-model LDVs in general are already equipped to deal with worst-case evaporative emissions.[90] Additional work may be needed to determine the effect of evaporative emissions (e.g., permeation) if FFVs use M-60 blends. Given the more aggressive nature of methanol on materials, additional costs may be necessary to ensure materials compatibility of evaporative control systems.

Emissions issues are quite complex; an entire report might be warranted solely for this subject. Few credible data appear to exist regarding the emissions implications of using GEM blends in existing FFVs or conventional LDVs. Further research, testing, and studies are needed. Notably, this report's focus is on converting in-use late-model FFVs or LDVs to use GEM fuels. This is important because manufacturers seeking to certify conversion kits can demonstrate compliance with emissions standards met by the pre-conversion vehicle, instead of more-stringent standards that apply to new vehicles.

3.6 Potential Cost / Price for FFV Conversion Kits

3.6.1 Manufacturing Costs and Selling Price

As previously described, E-85 FFVs require certain special components and/or modifications to accommodate ethanol-gasoline blends. Given the greater component commonality that exists today, the actual extra cost of manufacturing today's commercialized E-85 FFVs compared to gasoline vehicles may be approaching zero. Moreover, OEMs have priced FFVs and non-FFV versions of their products essentially the same. This is largely a function of production volumes; domestic OEMs have committed to produce 50% of their vehicles as E-85 FFVs. In addition, producing E-85 FFVs has certain advantages to OEMs.[91]

Estimates vary regarding the incremental cost of volume-manufacturing FFVs with the added capability to use M-85. A recent MIT study estimated this cost to be from \$200 to \$300;[92] the Methanol Institute estimate ranges from \$150 to \$300.[93] Both estimates assume a fuel sensor will be needed to accommodate use of M-85, E-85, gasoline, or any combination of these fuels. However, there appear to be numerous unknowns, especially regarding the extent to which LDV manufacturers are already manufacturing cars that can properly operate on multiple liquid fuels (refer back to Section 3.3.3). A key fuel-side issue is if GEM fuels can be limited to M-60; this would affect vehicle strategies and other factors that dictate cost.

As noted, this report focuses on aftermarket conversion strategies to displace petroleum usage in America's in-use LDV fleet. Presumably, if the installed price of a GEM fuel conversion system provides an attractive payback period, many end users will be willing to pay to convert their in-use vehicles. The price of conversion kits will be heavily impacted by at least two factors: 1) the extent to which existing vehicles are already materials compatible with ethanol and methanol

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[90] Notably, no FFVs have yet been certified to California's Partial Zero Emissions Vehicle (PZEV) standard, which must emit zero evaporative emissions for 150,000 miles. However, this is not relevant in a strategy to convert in-use vehicles.

[91] Some of the OEMs' higher FFV costs are being offset by current incentives in CAFE regulations.

[92] Massachusetts Institute of Technology, "The Future of Natural Gas: an Interdisciplinary MIT Study," August 2011, accessed online at: http://web.mit.edu/mitei/research/studies/documents/natural-gas-2011/NaturalGas_Report.pdf.

[93] Greg Dolan, Methanol Institute, "Methanol Transportation Fuels: A Look Back and Forward," presentation at the International Sympsia on Alcohol Fuels, September 27, 2005. Accessed online at http://www.eri.ucr.edu/ISAFXVCD/ISAFXVPP/MTFLBLF.pdf.

(M-60?), and 2) the costs to manufacturers for achieving conversion kit certification with EPA and/or CARB (see the detailed discussion in Section 4).

As described, at least one company has certified an E-85 FFV conversion kit and is selling it for approximately $1,000 (self installed) or $1,900 with installation included. Notably, a GEM fuel conversion kit is likely to be more expensive. Gasoline-ethanol-methanol engines can involve greater combustion and emissions tradeoffs and pose special challenges, not the least of which is meeting evaporative emissions requirements.[94] Materials compatibility challenges are also greater when FFVs are designed for methanol in the fuel blend. These unknowns make it difficult to accurately estimate how much it would cost to certify and sell FFV conversion kits designed for GEM fuels.

3.6.2 Lifecycle Costs to End Users

Lifecycle costs to end users for converting an LDV or FFV to use GEM fuels will be dictated by capital costs (previous subsection) and "O&M" (operation and maintenance) costs. O&M costs will largely be dictated by fuel prices, which are variable and strongly influenced by feedstock. Refer to Section 3.3 for a broad discussion of common and emerging feedstock for ethanol and methanol.

As previously noted, the prices of ethanol, methanol, and gasoline fluctuate depending on many factors. Currently, the national average price for E-85 is about $3.47 per gasoline gallon equivalent (GGE). Depending on where the E-85 is purchased, the current cost of gasoline, and the relative efficiency that is achieved when combusting both fuels, it can be more or less expensive to operate a current-technology FFV on E-85 compared to gasoline (E-10). While methanol (M-85 or M-60) is not currently sold as a transportation fuel in North America, it is widely marketed as a chemical commodity. The current price in North America for M-100 through September 2012 is $1.32 per gallon[95], or about $2.68 per GGE. As long as the price of natural gas is low, the price of methanol is likely to stay low.

This highlights the potential for relatively cheap methanol to be used in GEM-fuel-capable LDVs, as part of a strategy to facilitate petroleum displacement in America. Such a strategy will be feasible if life-cycle costs provide an acceptable payback period for end users; this will most likely require a minimized capital cost and availability of inexpensive methanol fuel. Today, large-scale production of methanol from natural gas is a well developed technology that is likely to yield very competitive methanol prices for blending in transportation fuel.[96] Recent improvements in extraction technology from shale deposits have substantially increased accessible reserves of natural gas in the United States (and other countries). Notably, methanol production will have to compete with the direct use of natural gas as an alternative transportation fuel, and interest in the latter is peaking. Methanol derived from coal is not currently considered to be a viable transportation fuel strategy, because of the relatively high GHG emissions associated with this production pathway.

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[94] See for example "GM Update on Flex-Fuel Vehicle Challenges in CA," Power Point presentation available online at: http://www.ethanolmt.org/presentations/27-Al%20Weverstad%20presentation.ppt#276,1,GM Update on Flex-Fuel Vehicle Challenges in CA.

[95] Methanex Corporation, "Methanex Regional Posted Contract Prices," accessed on line on September 4, 2012 at http://www.methanex.com/products/methanolprice.html

[96] L. Bromberg and W.K. Cheng, Methanol as an Alternative Transportation Fuel in the US: Options for Sustainable and/or Energy-Secure Transportation," Massachusetts Institute of Technology, Sloan Automotive Laboratory, November 2010.

As with alternative fuels in general, fuel-side logistics and economics present equal or greater challenges than vehicle issues. Today there are no public methanol fueling stations in America, and methanol's direct use as a vehicle fuel is limited to race car applications. Unlike ethanol, methanol lacks any strong advocacy group for its existence as a transportation fuel. Key questions include: How will this change? Through what commercialization path will methanol be reintroduced to LDV fuel markets? What entities will provide political will and commit major resources?

4. Requirements to Achieve Certification for Alternative Fuel Conversion Systems

The objective of this task was to review EPA and ARB regulations regarding alternative fuel conversion systems, and provide a high-level summary of relevant regulations and compliance measures. This helps understand the opportunities, barriers and costs associated with certifying and marketing alternative fuel conversion systems for application to in-use LDVs in the United States.

4.1 Process to Obtain EPA Certification

EPA and other federal government agencies recognize the potential legitimacy of converting existing gasoline vehicles into FFVs that can be operated on alcohol fuels, gasoline, or any mixture of the two. However, the U.S. DOE provides the following advice to those who are considering undertaking this process (emphasis added in **bold text**):

> *"Converting a conventional gasoline vehicle to a flex fuel vehicle requires extensive modifications throughout the fuel system and electronic engine-control system. Any change to a vehicle or engine that could potentially affect exhaust or evaporative emissions requires certification with the appropriate air quality authority. Manufacturers must go through a certification process to ensure their systems will not have a negative effect on emissions. Emissions standards are fuel neutral, which means that the same emissions requirements apply no matter which fuel powers the engine or vehicle. Therefore, to comply with emissions standards,* ***converted vehicles and engines must demonstrate that they meet the same emissions standards*** *that the original equipment manufacturer vehicle met.*

Demonstrating that a converted vehicle still meets its original emissions standards is a higher standard to meet than merely demonstrating that its emissions did not increase, as is required for fuel economy retrofit devices (Section 2). In essence, manufacturers of alternative fuel conversion systems must go through a certification process much like the one that applies to new vehicle certification (with some recent adjustments). This includes more-extensive emissions testing and demonstration of tough durability requirements as well as on-board diagnostics (OBD) compliance testing. Conversion system manufacturers must obtain a Certificate of Conformity from EPA that ensures compliance with EPA requirements and serves as an exemption from Clean Air Act anti-tampering requirements.

Each certification applies to a single conversion system in a specific common group of vehicles (e.g., engine families); in other words, the conversion systems by themselves are not certified. The federal government notes that using non-certified conversion system / vehicle combinations "is illegal and may affect warranties." Alternative fuel system manufacturers must ensure that conversions are performed by properly trained and authorized technician. All equipment must be "safe, durable, and meet the appropriate emissions standards."[97]

Recently (April 2011), EPA streamlined its rules for alternative fuel converters using a three-tiered approach based on vehicle age/useful life. The intent was to "streamline the compliance

[97] U.S. DOE (National Renewable Energy Laboratory), "Flexible Fuel Vehicle Conversions," accessed online at NREL website, June 2012, http://www.afdc.energy.gov/afdc/vehicles/flexible_fuel.html?0/E85/.

process" affecting manufacturers of vehicles and/or conversion systems, "while maintaining environmentally protective controls." Specifically, EPA amended the regulatory procedures in 40 CFR part 85 subpart F and part 86 to introduce new flexibilities for all clean alternative fuel converters, and expanded compliance options in certain conversion situations. EPA acted with the expectation that the new procedure would "result in a cost savings to many converters" of AFVs.[98]

EPA's revised vehicle fuel conversion certification process entails the following tasks:

- Review all applicable regulations (40 CFR part 85 subpart F)
- Set up a meeting with EPA to discuss compliance plans (recommended by EPA)
- Follow regulations to select worst-case emission data vehicle/engine to represent conversion test group/engine family and evaporative/refueling family
- Conduct all necessary testing, following all federal test procedure regulations (40 CFR part 86, subpart S and subpart B for light-duty and heavy-duty chassis)
- Submit all required information to EPA through the Verify Information System
    - Obtain manufacturer's code with Verify
    - Select demonstration category and corresponding process
    - Embed related documents required by regulations
    - Log in to Verify and submit the completed data submission form to the Verify Document Module
- After receiving confirmation from the certification applicant that the data submission form and its embedded documents were successfully uploaded to the Verify data system, EPA processes complete submissions. EPA notifies the applicant if / when a given test vehicle or engine has been selected for confirmatory testing.

There are a number of features adopted by EPA in March 2011 that make this "age-based program" less onerous and costly to entities seeking to certify AFVs and conversion systems. A key difference is that the new rules no longer require converters to renew (recertify) a given vehicle's certificate. Essentially, EPA's revised process acknowledges that "it's appropriate to treat alternative fuel conversions differently, based on the age of the vehicle or engine being converted." Under the new regulations, testing and compliance procedures differ based on the age category of the vehicle or engine that is converted: new and relatively new, intermediate age, or outside useful life. Table 6 summarizes EPA's new age-based certification requirements.[99]

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[98] http://www.epa.gov/otaq/consumer/fuels/altfuels/conversions-fr-webinar.pdf
http://www.epa.gov/oms/consumer/fuels/altfuels/420b11017.pdf

[99] http://www.epa.gov/otaq/verify/documents/alt-fuel-user-guide-20090121.pdf

Table 6. Overview of EPA Retrofit Age-based Certification Requirements

Overview of Program Elements					
Vehicle/Engine Age			**Conversion Manufacturer Requirement**		**Certificate Issued?**
Category	**Applicability**	**Example for 2011**[1]	**Demonstration**	**Notification**	
New	MY >= current calendar year - 1	MY 2010, 2011, 2012 and < useful life mileage	Exhaust, Evap, and OBD testing[2]	Certification application	Yes
Intermediate age	MY <= current calendar year - 2 and < useful life	MY 2002, 2003, 2004, 2005, 2006, 2007, 2008, 2009 and < useful life mileage	Exhaust and Evap testing[2] + OBD scan tool test and attestation	Compliance submission[3]	No
Outside useful life	Exceeds useful life	MY2001 and older or > full useful life in mileage	Technical justification[4] and OBD scan tool test and attestation	Compliance submission[3]	No

Note:

[1] This example is for light-duty Tier 2 vehicles operating in the 2011 calendar year which have a useful life of 10 years or 120,000 miles.

[2] Exhaust and evap refers to all exhaust emission testing and all evaporative emission and refueling emission testing required for OEM vehicle/engine certification, unless otherwise excepted. OBD testing refers to all OBD demonstration testing as required for OEM vehicle/engine certification.

[3] The compliance notification process for intermediate age and outside useful life conversions will be electronic submission of data and supporting documents.

[4] The technical justification may include data from exhaust and evaporative emissions testing.

4.2 Process to Attain CARB Alternative Fuel Conversion Certification

The following enumerates the basis steps and process to attain CARB certification for an alternative fuel conversion system / vehicle combination[100]:

- Review Final Regulatory Order (1995) Alt Fuel Retrofit (all vehicles regardless of their age) http://www.arb.ca.gov/msprog/aftermkt/altfuel/altfuelsysreg.pdf
- Request for certification of an alternative fuel retrofit system
  - Description of engine families for which retrofit system is designed for
  - Description of alternative fuel retrofit system
  - Procedures for installing and maintaining the retrofit system
  - Agreement to supply ARB one or more vehicles used for certification testing
- Perform target emission standards testing
- Perform OBD compliance testing
- Provide extended manufacturer warranty with high cost parts list
- Prepare durability plan/testing/deterioration factors (Manufacturers Advisory Correspondence)
- Perform Confirmatory testing
- Meet general Requirements: Fuel lockoff valve, Possible independent laboratory evaluating driveability, Possible analysis showing modifications to OBD were not adversely affected, Emission control labels, Owner's manual, Manufacturer recordkeeping requirement, and Installer recordkeeping requirement

[100] http://www.arb.ca.gov/msprog/aftermkt/altfuel/altfuelsysreg.pdf

Once approved, CARB issues an Executive Order certifying that the aftermarket system can legally be sold in California (or other jurisdictions under CARB requirements). CARB can conduct in-use emissions testing at any time to ensure that its requirements have been met, and emissions are not being increased by the aftermarket system.

4.3 Overview of Differences in Certification Procedures

EPA and CARB have separate, related processes to certify alternative fuel conversion systems. The discussion that follows can help better understand agency-specific challenges that exist in bringing alternative fuel conversion systems to market.

Important Note: CARB has adopted stricter air quality regulations and requirements due to the extreme nature of California's unhealthful air quality, and the daunting challenge to attain National Ambient Air Quality Standards by federal and state deadlines. CARB staff continue to be world leaders towards advancement of mobile source air pollution control technologies and the restoration of healthful air quality in urban areas. This section does not intend to imply that CARB's rigorous motor vehicle certification requirements are unwarranted. Rather, it presents perspectives of industry stakeholders who believe certain changes are needed to assist small-volume manufacturers with expanded deployment of AFV conversion systems that can further the cause of various national and state objectives.

Manufacturers seeking EPA and CARB certification typically undergo the process with both agencies simultaneously. When comparing the EPA and CARB certification processes that must be met to convert new LDVs for alternative fuel operation, OBD validation stands out as the most-consequential difference. The CARB process requires greater resources for preparing an OBD compliance plan, and significant additional validation tests and reports beyond EPA's requirements. In addition, CARB imposes other requirements beyond EPA involving areas such as environmental performance and anti-tampering labeling. The next section discusses the cost implications of EPA and CARB requirements.

4.4 Costs to Certify Conversion Systems

Meeting air pollution certification requirements imposed by EPA and CARB entails significant costs that are borne by the manufacturer. As Table 7 summarizes, it can cost an estimated $230,000 to successfully certify a LDV alternative fuel conversion system with both EPA and CARB. For the certification procedures and requirements under both agencies – but especially with respect to CARB's – the major cost component relates to OBD demonstration testing. Almost 70% of the total certification costs are associated with OBD demonstration testing, travel, vehicle shipments, and application preparation.

Table 7 Estimated Costs for One New Vehicle Retrofit Certification (EPA and CARB)

	Testing Costs	Labor Hours	Labor Costs	Total Costs
Exhaust Tests	$6,258	242	$16,287	$22,545
Evaporative Tests	$6,369	247	$16,576	$22,945
OBD Demo Tests	$26,317	1,019	$68,496	$94,812
Travel, Shipments, Application Preparation	$16,867	653	$43,901	$60,768
Certification Fees	$8,000	310	$20,822	$28,822
TOTAL	$63,810	2,472	$166,082	$229,892

While such costs are not overwhelming to large OEMs certifying mainstream LDV platforms on gasoline, small volume manufacturers that sell aftermarket alternative fuel conversion systems find it much harder to amortize such costs.

According to stakeholder input, CARB's standards are more stringent (and costly to meet) than those of EPA. As noted, California has been granted a "waiver" under the federal Clean Air Act to adopt stricter air quality regulations and requirements, given its extreme non-attainment status for ambient air quality standards. Many other states have chosen to adopt California's emissions requirements, including its certification provisions for alternative fuel conversion kits.

4.5 Potential Approaches to Simplify or Streamline Compliance Requirements

This section summarizes ways that the regulatory process to certify aftermarket alternative fuel conversions could potentially be simplified or streamlined. Based on comments from industry stakeholders, improving or streamlining CARB's certification process is of greater priority than EPA's certification process.

Industry stakeholders were asked about possible approaches to simplify or streamline CARB's compliance requirements. Those recommendations, which do not necessarily reflect TIAX's opinion, are provided in the next section.

5. Conclusions and Recommendations

This assessment provides a high-level perspective on the feasibility of reducing gasoline consumption in America's existing LDV fleet through two distinct types of retrofit technologies. Specifically, it examines the opportunities and challenges of using aftermarket retrofit systems to 1) improve fuel efficiency of late-model LDVs, or 2) convert them to "flexible fuel vehicles" that can use fuel ethanol (E-85), fuel methanol (M-85), or "GEM" (gasoline-ethanol-methanol) blends. Conclusions and recommendations (if any) for both approaches are summarized below.

5.1 Aftermarket Retrofit Devices to Improve LDV Fuel Economy

The first part of this study assesses the opportunities and challenges of developing retrofit devices to improve the fuel economy of in-use LDVs. We conclude the following:

- Such devices have been commercially available in the U.S. for decades. Both EPA and CARB have conducted testing programs to assess whether they increase the emissions of vehicles on which they are installed. However, neither EPA nor ARB approves, certifies or endorses the ability of retrofit devices to improve fuel economy; in fact, both agencies urge consumers to exhibit significant skepticism about their efficacy. In fact, EPA warns consumers that *"any additions or changes to your car's engine, emission system, fuel system, or exhaust system have the potential to increase emissions, reduce fuel economy, cause harm to the converted car, void its manufacturer warranty, create safety or environmental hazards, and/or violate the federal prohibition against tampering"*

- The reality is that these devices are routinely being sold in the U.S.; this suggests that the above warnings tend to represent worst-case situations. The petroleum-saving benefits (if any) of devices currently on the market are difficult to corroborate without extensive testing under controlled conditions. However, it is clear that major societal benefits can be realized if one or more retrofit device proves to be affordable, legal, and highly effective at increasing the fuel economy of in-use LDVs. Of course, there are significant challenges to manage; most stem from the inherent tradeoffs associated with simultaneously achieving improved fuel economy, low emissions, acceptable performance, and safety requirements. Maintaining viability of the base vehicle's OEM warranty is a gray area that requires careful attention.

- The Max Energy CON™ manufactured by Hypertech provides a kit to reflash the ECU of selected LDV models. It is roughly estimated that 12 to 35 million in-use late-model LDVs could potentially be compatible with using this basic technique to modify software to achieve fuel economy improvements. It appears from available evidence that installing this particular device on an EPA-certified vehicle using the recommended procedure does not constitute tampering or void the vehicle's original warranty (assuming no provable harm is caused to the base vehicle). Hypertech makes the claim that a 14% fuel economy increase (roughly) can be achieved by installing this device on late-model LDVs. No proof was provided to corroborate this claim. If this information is accurate and representative, the cost of the Energy Max E-CON™ device (about $380, installed) can be paid back from fuel savings within about one or two years. Current annual sales of this device are proprietary and therefore unknown.

- If a new retrofit device is introduced that has major, cost-effective fuel economy benefits, the biggest potential challenge may involve how to convince potential end users. Neither EPA nor CARB appears to have found definitive proof that aftermarket devices significantly improve fuel economy while not increasing emissions levels. Both actively encourage consumers to be skeptical about any claims to the contrary. Another challenge for marketing aftermarket devices is the need to avoid unacceptable tradeoffs noted above. If these tradeoffs are not adequately managed by the device manufacturer, the result may be negative consumer feedback (e.g., poor drivability) and reduced ability to sell product.

5.2 Aftermarket Systems to Convert for Flex Fuel Operation

The second part of this study assesses the opportunities and challenges of marketing systems that can cost effectively convert in-use FFVs (or even conventional LDVs) to operate on gasoline-alcohol blends that could include methanol. The assessment focuses only on vehicle-side issues and does not address the equally important fuel infrastructure side.

We conclude the following:

- E-85 FFVs represent the current market in North America for FFV technology, but the same basic issues regarding potential to convert vehicles also apply to M-85 FFVs. Significant differences involve 1) the lower energy content of M-85 relative to E-85; and 2) the greater materials compatibility challenges presented by methanol versus ethanol.

- Aftermarket (retrofit) systems to convert conventional gasoline LDVs into E-85 FFVs use similar technology as found in OEM FFVs. In a conversion system, a supplemental fuel injection system and an additional microprocessor may be needed. The supplemental microprocessor monitors various parameters (e.g., fuel, engine performance, and exhaust) to adjust the amount of fuel injected. As part of the certification process, the conversion kit manufacturer generally needs to prove that the converted vehicle will maintain the original vehicle's emissions certification, and that OEM components will not be harmed or negatively affected (e.g., reduced durability).

- A promising strategy for displacing petroleum in the in-use FFV / LDV fleet involves the potential use of gasoline-ethanol-methanol blends (so-called "GEM" fuels). GEM blends can be configured to have similar characteristics as E-85 / gasoline blends, and can potentially offer performance, logistical and cost advantages when used in existing FFVs (or conventional vehicles converted to FFV capability). Specifically, introduction of low-cost methanol (up to 60% methanol, or M-60) into gasoline-ethanol mixtures could potentially be a very affordable, effective gasoline-substitution strategy for America's large fleet of in-use late-model LDVs.

- Approximately eight million in-use FFVs are already designed to use E-85. The main (vehicle-side) technical issue for expanding their fuel usage to GEM blends involves methanol's greater corrosivity. Depending on the extent to which the fuel systems of modern E-85 FFVs are also compatible with methanol (up to M-60), millions of in-use FFVs could achieve greater petroleum displacement while being operated at lower annual fuel costs.

- A significant percentage of America's existing conventional gasoline LDVs (non-FFVs) may also be compatible with GEM blends. Independently, some parties have attempted to demonstrate that "ordinary American cars" can readily be converted to operate on methanol and GEM fuels, with minimal vehicle changes, low costs and clear societal benefits. However, further investigation and testing would be needed – most likely under government oversight and highly controlled laboratory conditions – to advance this concept as a potential national strategy for reducing petroleum usage.

- Such testing would need to carefully investigate the effects of GEM blends on FFVs and non-FFVs for all critical issues according to all applicable testing protocols and standards that apply to LDVs undergoing fuel conversion. This would ideally include evaluations about remaining vehicle life and payback on investments. Notably, it may take new thinking and metrics to interpret the implications of such testing, e.g., how to treat tradeoffs in provision of strong societal benefits versus marginally reduced vehicle life.

- One company has certified an E-85 FFV conversion kit and is selling it for approximately $1,000 (self installed) or $1,900 with installation included. This Flex-Box Smart Kit™ is the only aftermarket FFV conversion device certified and approved by EPA (but not by CARB). A wide array LDV types are compatible to use this conversion kit, and it does not appear to void the original warranty, although damage to the base vehicle caused by alterations or modifications will not be covered.

- An FFV conversion kit capable of using GEM fuels is likely to be more expensive, due to greater materials compatibility issues and other special challenges. These unknowns make it difficult to accurately estimate how much it would cost to certify and sell FFV conversion kits designed for GEM fuels. If the life-cycle costs (capital costs, fuel, maintenance) of converting an LDV to operate on GEM fuels can provide potential end users with an attractive payback period (roughly three years or fewer), many may be motivated to convert their in-use vehicles.

- The price of "GEM fuel" conversion kits is difficult to accurately estimate, due to key unknowns. It will be heavily impacted by at least two factors: 1) the extent to which existing vehicles are already materials compatible with ethanol and methanol (up to M-60), and 2) the costs to manufacturers for achieving conversion kit certification with EPA and/or CARB.

5.3 Simplifying or Streamlining Compliance Requirements

A potential barrier to develop and market any fuel economy retrofit device or alternative fuel conversion kit for late-model LDVs involves costs associated with meeting regulatory compliance requirements and obtaining assurances against enforcement actions. Requirements to certify alternative fuel conversion systems are particularly costly, and are difficult for device manufacturers to amortize over relatively low production volumes. In particular, CARB has adopted strong air quality regulations, requirements and enforcement policies due to the extreme nature of California's unhealthful air quality, and the daunting challenge to attain National Ambient Air Quality Standards by federal and state deadlines. Clearly, it is necessary and warranted for CARB to have more rigorous motor vehicle certification requirements than EPA.

Notwithstanding CARB's special charter, industry stakeholders have suggested changes are needed in its system to assist small-volume manufacturers with expanded deployment of AFV conversion and/or retrofit systems.[101] They argue that such changes can advance the causes of various state and national objectives. Their recommendations, which do not necessarily reflect TIAX's opinion, are summarized as follows:

- Reduce CARB response time – Interviewed stakeholders believe that the turn-around time (60-90 days minimum) to receive an Executive Order is excessive. In addition to streamlining the process, some stakeholders believe CARB needs to add additional staff dedicated to this process. Input indicated that these changes could potentially bring CARB's turnaround time down to be in line with EPA's estimated turnaround time of about 25 days.
- Examine / streamline / reduce CARB OBD requirements – Stakeholders indicate that CARB's OBD testing process and requirements are especially costly and resource-intensive to meet. They argue that this process needs to be in closer alignment with EPA requirements. If OBD testing costs for CARB can be reduced down to those of the corresponding EPA testing, then the combined OBD testing costs for both agencies would drop very significantly.
- Consider special allowances for low-volume sales – CARB could consider allowing low-volume manufacturers below a certain sales threshold (e.g., up to 5,000 units per year) to default to EPA certification requirements. Achievement of CARB certification would be an additional requirement once that sales volume is exceeded.
- Consider easing requirements for FFVs (and bi-fuel vehicles) – Under the same special system noted above, CARB could consider allowing applicants to certify FFV and bi-fuel conversion systems under the EPA process, for low-volume California sales. This would help industry stakeholders while also furthering "bigger-picture" state objectives that include petroleum displacement, lower-carbon fuels, renewable fuels, and reduced greenhouse gas emissions. However, this does not address a key point: to displace large volumes of gasoline in America's in-use LDV fleet, it will take high-volume kit sales and conversions, thereby losing justification to ease requirements.

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[101] At the time this report was being finalized, CARB was considering changes to its certification requirements for alternative fuel conversion systems.