Methanol Fuel Blending and Materials Compatibility Report

Overview of TIAX Report on U.S. Marketplace

Introduction

The Methanol Institute employed internationally renowned consulting group TIAX to prepare a comprehensive report analyzing the myriad of factors and considerations inherent in using methanol as a transportation fuel and blending methanol with gasoline in the U.S. market. The report reaffirms that there are no technical barriers to the widespread adoption of methanol in transportation, and delves into the technical, regulatory and market drivers for the advancement of methanol fuels.

The purpose of this report was to look at the critical issues that must be addressed to introduce methanol as a substantive part of the transportation fuel pool for internal combustion engine vehicles. The report is broken up into two main sections of analysis – low-level fuel blending (up to M-15 fuel) and high-level blending (M-70 and above). Both approaches are delineated as viable options with their own unique considerations that must be taken into account in order to move forward effectively.

Highlighted Report Findings

Low-level Methanol Fuel Blends - This report looks at the viability of low-level methanol blending with gasoline, which would displace petroleum or ethanol based fuels on a volume basis. There is an existing federal waiver for up to 5% methanol with cosolvents to be used in gasoline, though TIAX determined that most states would require an ASTM standard and California in particular would require multimedia testing to begin blending. There is currently an ASTM standard in place for up to 2.5% methanol with cosolvents by volume in gasoline. Since gasoline or ethanol would be displaced on a volume basis in this scenario, methanol would need to be priced below the current price of gasoline or ethanol (both about $2.00 per gallon). Given methanol spot prices of just about $1.00 per gallon, this is potentially an attractive market.

High-level Methanol Fuel Blends – Methanol would be replacing petroleum fuels on an energy basis in a high-level blending scenario and accommodations would have to be made for materials compatibility. High-level blends incorporate a wide range of options, including M-70, which would perform very similarly to E-85 in flex fuel vehicles, M-85 and even neat methanol, or M-100. Displacing gasoline on an energy basis is a greater challenge given methanol's lower energy content. If using mixes above M-70, separate considerations would need to be made for materials compatibility and an upgraded fuel pump and fuel sensor may be necessary for some vehicles, which could raise the incremental cost of vehicles by up to $490.

This report demonstrates that methanol fuel is a viable and cost-effective choice for displacing petroleum based fuels in the transportation pool, but also indicates that more research is needed into specific topic areas to gain greater clarity. The effects of commingling ethanol and methanol in fuels needs to be further assessed. Additional research is also needed on material and engine changes necessary to existing ethanol FFVs to operate on methanol, ethanol, gasoline, or any mixture of these fuels.

4100 North Fairfax Drive, Suite 740, Arlington, VA 22203 – (703) 248-3636
Suntec Tower Three 8 Temasek Blvd Singapore 038988 – +65 6 866 3238
www.methanol.org
Prepared October 2010

Methanol Fuel Blending Characterization and Materials Compatibility

Final Report

Report for
Methanol Institute
4100 North Fairfax Drive
Suite 740
Arlington, VA 22203

Date: August 27, 2010 Rev A

Prepared by
Philip Sheehy, PhD
Karen Law
Michael D. Jackson

TIAX LLC
20813 Stevens Creek Blvd., Suite. 250
Cupertino, California 95014
Tel 408.517.1550
Fax 408.517.1551

TIAX Case No. D5607

Table of Contents

Summary

Methanol has two avenues to pursue in the current transportation market: methanol in a low level blend strategy (less than or equal to 15 percent methanol by volume) or in a high level blend scenario (greater than or equal to 85 percent methanol by volume, including as a neat fuel). The benefits, barriers, and issues are defined as technical, regulatory, and market economic. Furthermore, the benefits, barriers, and issues vary depending on whether methanol is used in a light-duty application (e.g., passenger cars) or in a heavy-duty application (e.g., trucks or buses).

The most significant difference between the two blend strategies is based on the pricing. In a low level blend strategy, methanol would displace gasoline, ethanol, or a fuel additive on a volumetric basis. In this scenario, methanol would need to be priced competitively on wholesale volumetric basis with gasoline, ethanol, or other fuel additives. On the other hand, in a high level blend strategy, methanol would displace gasoline or diesel at the pump. In this case, methanol must be priced at the pump (including taxes and other costs) to compete on an energy basis with gasoline or diesel.

The pricing strategies for the two blend scenarios present an interesting set of tradeoffs. For instance, the high level blend strategy may provide higher volumes for the methanol industry in the long-term. However, methanol will likely be sold at a lower price than if a low level blend strategy is pursued. The price difference is the result of the volume versus energy basis. The strategies are also not mutually exclusive. If both the low and high level blend strategies are pursued simultaneously, then the high level blends would experience upward price pressure from the low level blends, assuming that gasoline and ethanol are priced higher than methanol. Eventually, the industry would have to settle on a single price for methanol. The factors that influence the settled price are based on other factors unique to each blend strategy e.g., infrastructure and vehicle availability.

The methanol experience in California during the 1980s and 1990s provided valuable lessons. At the time, methanol was being promoted as a cleaner alternative to petroleum derived fuels and as a petroleum displacement strategy. Reformulated gasoline drastically changed the market, and methanol providers were presented with a stark reality: methanol had a difficult time competing with gasoline and diesel as a neat fuel or as a high level blend due to the low prices of oil and the lower energy density of methanol. Around the same time, MTBE (with methanol as a feedstock) –as an oxygenate for gasoline–presented itself as an opportunity to capture a significant market. In this strategy, the methanol industry capitalized on a higher value market because it was being sold on a volume basis as a feedstock for MTBE, rather than on an energy basis as a neat fuel.

The most important determinant in today’s market will be the pricing of a methanol fuel strategy, which includes the cost of methanol, the cost of infrastructure development (e.g., fueling stations), and the cost of methanol compatible vehicles. Together, these cost factors will determine the lifecycle costs of methanol. We also discuss other drivers and barriers in context of the technical, regulatory, and market economic constraints of the U.S. transportation fuels market today.

Technical Issues

- For low level blends, the primary technical issue is commingling of a) various reformulated gasoline blendstocks for oxygenate blending (RBOBs) and b) different low level ethanol blends or mixed methanol-ethanol low level blends.
- For high level blends, materials compatibility is the main issue. These issues are generally well understood and do not represent a significant barrier except in existing vehicles.

Regulatory Issues

- There is a waiver on record for methanol as an additive to gasoline at the federal level. However, in a low level blend scenario, methanol faces two significant challenges:
  - Most states will require an ASTM standard and test procedure for low level blends of methanol with gasoline.
  - California explicitly prohibits the use of methanol as an oxygenate in gasoline without a full multimedia evaluation impact analysis.
- There are no significant regulatory issues that limit the potential of high level blends.

Market Economic Issues – these focus on issues other than cost discussed above.

- Methanol in a low level blend strategy, regardless of its feedstock, has a small but limited potential to displace petroleum, as it is more likely to displace ethanol today than gasoline.
- Methanol in a high level blend strategy, derived from natural gas, coal, or biomass, has significant potential to displace petroleum; however, this is dependent on vehicle availability and fueling infrastructure development.
- Advances in gasoline formulation and internal combustion engines (ICEs) have essentially eliminated the air quality benefits that were reported in the early development of methanol as a fuel. The recent emphasis on mitigating climate change through reductions in greenhouse gas (GHG) emissions is an important driver. Methanol has the potential to reduce GHG emissions in both a low and high level blend if it is produced using a renewable or waste feedstock.
- The lifecycle cost savings potential of a high level blend of methanol in the light- and heavy-duty sector varies from small to significant. However, the savings potential is highly dependent on a coordinated strategy to develop the required fueling infrastructure and the manufacture of vehicles that run on methanol.
- The perception of methanol with policy makers in California, and to a lesser extent with policy makers at federal regulatory agencies is a barrier to adoption. The recent concerns raised regarding the potential GHG emission impacts of increased corn ethanol use may improve the market position of methanol. Similarly, a recent increase in natural gas reserves, the primary feedstock for methanol, in the United States may also improve the market position of methanol as it becomes a growing domestic resource.

Introduction

The objective of TIAX's research was to investigate methanol fuel blends in the context of today's alternative fuels market to determine which blends have the highest likelihood of success in the U.S. marketplace. Our work was conducted over a series of 3 tasks:

Task 1 – Methanol Blend Characterization

Task 2 – Recommend Methanol Fuel Blends

Task 3 – Review and Research Materials Compatibility with Methanol

In the following sections we review our research regarding methanol fuel blends in the context of the a) technical, b) regulatory, and c) market economic issues for methanol as a transportation fuel. This work is primarily a literature search, but TIAX also reached out to staff at regulatory agencies to clarify or elucidate various issues. Our objective of Task 1 was to provide the background and context necessary to make informed recommendations in Task 2. The outcomes of Task 1 and Task 2 provided the most appropriate information regarding materials compatibility for Task 3.

We focused our scope in two areas for the sake of organization and clarity. Firstly, we considered issues at the federal level and issues that are unique to California – the largest transportation market (by volume) in the United States. Secondly, we distinguished between issues that affect a) low level blends of methanol, less than or equal to 15 percent by volume, and b) high level blends of methanol, greater than or equal to 85 percent by volume, and c) both low and high level blends.

The remainder of this report is divided into the following 5 sections:

1. **Technical Issues**: Our scope in this section includes technical issues as they relate to new vehicles and new infrastructure, as well as the existing fleet and existing fueling infrastructure, and fuel additive constraints.
    a. For low level blends we review gasoline reformulation and methanol as an additive/oxygenate.
    b. For high level blends, we discuss materials compatibility in both vehicles and the fueling infrastructure.
    c. For low and high level blends, we discuss the reduced energy density of methanol.

2. **Regulatory Issues**: We frame the current regulatory landscape for alternative transportation fuels in the context of California state and federal legislation, standards, policies, and incentives. With regard to vehicles, we focus on standards and policies intended to reduce criteria pollutant tailpipe and evaporative emissions.
    a. For low level blends we discuss the Clean Air Act provisions related to fuel additives registration and the California Reformulated Gasoline Regulations.

b. For high level blends we discuss the Open Fuel Standard Act and the 2010 Emission Regulations for Heavy-Duty Vehicles in California.

c. For low and high level blends we discuss the federal Renewable Fuel Standard (RFS2, part of the Energy Independence and Security Act of 2007), the zero emission vehicle (ZEV) standards in California, the Low Carbon Fuel Standard (LCFS) in California, and federal incentives.

3. **Market Economic Issues**: Our discussion in this section provides the context of the challenges that face methanol in the transportation fuels market. The most significant challenge for methanol is fuel price, which will vary depending on the blend strategy. In a low level blend strategy, methanol will be priced to be competitive with gasoline, ethanol, and other fuel additives on a volumetric basis; in a high level blend strategy, methanol will be priced to compete with gasoline or diesel at the pump on an energy basis. Apart from the fuel price concerns, we focus on market drivers e.g., policy goals, and market challenges e.g., infrastructure development, for both low and high level blends. Section 3 is organized differently than the other sections due to the overwhelming significance of fuel price.

   a. In this subsection we discuss the pricing constraints that emerge from low and high level blend strategies, with reference to the California experience in the 1990s.

   b. In this subsection we discuss market drivers other than price, and how they impact low and high level blends. Our discussion includes the potential for petroleum displacement, emission reductions, infrastructure readiness, vehicle availability, and consumer perception.

4. **Review of Materials Compatibility with Methanol**: This section summarizes our research on the possible material compatibility issues with methanol for vehicles and fueling stations. This work was performed in two parts. The first effort was to review experiences from the previous work to develop and market methanol FFVs. We contacted individuals and reviewed publications on the development of both ethanol and methanol FFVs. The second part of this section covers a literature review on material compatibility issues with methanol.

5. **Recommendations**: Based on the work performed on the technical, regulatory, market economics, and material compatibility, we provide a list of recommendations that we believe will help to open up the opportunities for methanol as a transportation fuel. These recommendations focus on the research and development needed for methanol to be successfully used in both light and heavy duty vehicle application and distributed safely to the transportation market.

1. Technical Issues

The technical issues for methanol are generally well understood. The California experience in the 1980s and 1990s provided a valuable platform to develop a sound knowledge base for methanol use: flexible fuel vehicles (FFVs) capable of running on gasoline and methanol were commercialized, fueling stations were built, and this was done at scale, not on a trial basis. The primary technical issue for methanol use in a low level blend strategy is gasoline formulation, whereas for a high level blend it is materials compatibility (which will be explored in more detail in Section 4, and is only summarized here). The lower energy density of methanol (as compared to gasoline and diesel) is an issue in a high level blend strategy, and less so in a low level blend strategy. None of these three issues is considered a significant barrier: the technical issues are well documented and widely understood.

1.1 Low Level Blend Strategy

Most of the gasoline in the U.S. is blended with some level of ethanol. Based on the requirements of the Renewable Fuel Standard (see Section 2), ethanol (or other designated biofuel) will need to be blended into the entire gasoline supply. The introduction of reformulated gasoline (RFG) has been a significant market driver for low level blends of oxygenates like ethanol and methanol.[1] The most significant technical challenge for low level blends of methanol relates to strict limits on commingling of RBOBs, which only affects regions marketing different gasoline formulations. In order for low level blends of methanol to enter the marketplace, information regarding how low level blends of methanol and ethanol commingle needs to be developed. Note that the emission requirements of the blended/oxygenated fuel are a regulatory issue; however, the development of the appropriate RBOB is a technical issue that must be addressed.

Outside of the reformulated gasoline markets in the U.S., the technical barriers for methanol blended with gasoline are based on complying with basic gasoline formulation requirements. This is a cross-over issue that is both technical and regulatory.

1.2 High Level Blend Strategy

The most challenging technical issue for a high level blend strategy is the materials compatibility on the vehicle side and with the fueling infrastructure on the fuel delivery side. In high level blends of methanol, wetted surfaces in vehicles and fueling equipment must have compatible materials. For example, polyurethane is a common material used in vehicles that reacts strongly with methanol and should be replaced by elastomers that are compatible with methanol. Extensive testing of materials compatibility has been performed in the past for a range of methanol blend levels, and automakers have successfully adapted vehicle models for methanol fuel. From the mid-1980s to the late 1990s, Ford, Chrysler, and GM offered methanol compatible flexible fuel vehicles (FFVs), selling over 15,000 vehicles. Similarly, Detroit Diesel

---

[1] The US EPA not longer requires oxygenates for RFG, but refiners are still marketing ethanol RFG to partially meet the RFG standards, but mostly to meet the Renewable Fuel Standard.

manufactured a heavy-duty engine for transit and school buses, selling hundreds in California. These methanol compatible vehicles, along with the corresponding fueling infrastructure, have disappeared. The lesson from that period, however, was that methanol internal combustion engine vehicle (ICEV) technology was not the bottleneck to development of the methanol fuel market. The experience in California and elsewhere also demonstrated that there are no technical barriers on the infrastructure side for methanol.

The delivery and storage of methanol has similar constraints as discussed on the vehicle side. Methanol has unique materials compatibility issues that must be addressed with storage tanks, piping, dispensers, hoses, nozzles, emission control equipment, etc.

Since the work performed the 1990s, emission standards have become much more stringent for both vehicles and fueling stations. Gasoline technology is approaching near zero emissions for exhaust and evaporative emissions. Similarly, Stage II vapor recovery at fueling stations is required in most regions. The higher vapor pressure of low level methanol gasoline blends is a challenging technical issue for vehicle and equipment suppliers.

Fuel volatility is a problem that occurs in low level and high level blends. In low level blends small addition (5 percent) of methanol increases the gasoline methanol vapor pressure (RVP) to 12.5 psi (or about 3.5 psi) for a 9 psi gasoline. EPA regulates summertime gasoline volatility to control evaporative emissions and reduce ozone production. For high level blends the same issue occurs in FFVs that are using combinations of gasoline and methanol. At the low methanol gasoline blends higher evaporative emissions have to be designed for. The vehicle has to be designed to control evaporative emissions operating on gasoline (say at 9 psi) and M85 (around 7.5 psi), but also the highest RVP (12.5 psi) at 5 percent methanol. The issue is further complicated since most gasoline today is already blended with ethanol. Further research would be needed to investigate the possible effects of blending methanol with ethanol gasoline blends.

1.3 Issue(s) Affecting Both Strategies

Methanol’s energy density is about half of gasoline and diesel: 56,600 Btu per gallon compared to about 116,000 and 128,000 Btu per gallon, respectively. In the low level blend strategy, this becomes an issue as the blend approaches 15 percent, at which time the consumer may experience up to a 7.5 percent drop in fuel economy. Some – but not all – customers will start to notice the corresponding change in fuel economy, which at that point will become a significant issue regarding the price of the fuel (see Section 3 for more discussion of market economic issues).

For the higher level blends, the low energy density can be accommodated by improved fuel efficiency for dedicated vehicles, larger on-board fuel tanks, and/or more frequent refueling. These technical fixes, however, are small compared to the fuel cost as a driver, which is discussed further in Section 3 below.

2. Regulatory Issues

The regulatory landscape for fuels is driven by efforts to improve and/or maintain air quality, and more recently, to reduce GHG emissions that cause climate change. For air quality, regulations are generally targeted at tailpipe and evaporative emissions. For climate change, regulations are targeted at reducing the carbon intensity of fuels on a lifecycle basis, reducing tailpipe carbon emissions, and improving fuel economy. In both cases, there are a mix of standards and regulations at the federal level and in California that should be considered. An overview of the federal and California-specific regulations that are relevant for methanol is shown in Table 2-1.

Table 2-1. Overview of Relevant Federal and California-specific Legislation and Incentives

	Federal	California
Fuel Additives	Clean Air Act Amendments, waivers	Title 13, CA Code of Regulations, prohibited oxygenates
Fuel	Renewable Fuel Standard	Low Carbon Fuel Standard
Vehicle Emissions	Clean Fuel Vehicle Emission Standards MY 2010 HD Engine Standards Open Fuel Standard Act	Zero Emissions Vehicle Program Zero Emission Bus Regulation Low Emissions Vehicle Program

Our discussion in this section includes each of the regulations and incentives included in Table 2-1, organized based on their relevance to a) low level blends, b) high level blends, and c) both low and high level blends.

2.1 Low Level Blend Strategy

Regulations and Standards

The **Clean Air Act** requires that manufacturers and importers of gasoline, diesel, and **fuel additives** must register their product with the U.S. EPA to ensure their compliance with emission reduction goals. This legislation is significant to the integration of methanol in the fuels market because it: 1) requires a three-tiered registration process for blending of methanol in gasoline or diesel, and 2) gives the EPA discretion to grant or deny waivers from commercial introduction of new fuel additives, including increases in blending concentrations. Although various blends of up to 15 percent methanol have been requested to date, current EPA waivers limit methanol concentration in fuel blends to 5 percent with cosolvents. Table 2-2 lists the waivers that have been requested and their respective outcomes. The shaded cells indicate that a waiver was granted. Methanol is also registered as a fuel additive by five companies (Table 2-3).[2, 3] To increase the cap for methanol blending from 5 percent by volume, fuel providers will

[2] "Waiver Requests Under Section 211(f) of the Clean Air Act." U.S. Environmental Protection Agency. August 22, 1995.

Table 2-2. Methanol Waiver Requests under Section 211(f) of the Clean Air Act

Applicant (Docket #)	Fuel or Additive	Action	Date
Sun Petroleum Products Co. (EN 79-12)	Methanol/TBA (2.75% methanol-2.75% Butanol)	Conditionally granted	6/13/79
	Petition to revoke	Denied	11/10/80
Beker Industries (EN-79-20)	Crude methanol (0-15%)	Denied	4/11/80
Conservation Consultants of New England (EN-80-5/7)	Ethanol (5%)/Methanol (5%)	Denied	8/8/80
Anafuel Unlimited (EN-81-8)	"Petrocoal" (Methanol, Cosolvent alcohols with proprietary inhibitor)	Granted	9/28/81
	Petition to revoke	Proposal to reconsider	3/16/84
	Court vacates proposal to reconsider under 211(f)		12/4/84
	Court vacates original decision	Consideration of original waiver	7/26/85
		Original waiver denied	8/5/86
ARCO (EN-81-10)	Up to 4.75% Methanol/4.75% GTBA/3.5% oxygen	Granted	11/7/81
E.I. DuPont de Nemours & Company (A-82-33)	Methanol (0-3%)	Denied	2/18/83
American Methyl Corp. (EN-83-03)	"Methyl 10" (Methanol, Cosolvent alcohols and proprietary inhibitor)	Denied	11/14/83
E.I. DuPont de Nemours & Company (EN-84-06)	5% Methanol, 2.5% cosolvent alcohols, specified inhibitor	Conditionally granted	1/10/85
		Reconsideration	4/10/86
		Modifications of original conditions	10/22/86 5/13/87
AM Laboratories, Inc. (EN-87-05)	"AM 5/5," 5% methanol, 5% cosolvent alcohols, specific corrosion inhibitor	Denied	1/19/88
Texas Methanol Corp. (EN-87-06)	"OCTAMIX," 5% methanol, 2.5% (C2-C8) cosolvent alcohols, specified corrosion inhibitor	Conditionally granted	2/1/88
		Correction of cosolvent specifications	5/12/88
		Modification of original conditions	10/21/88

Note: The shaded cells indicate waivers that were granted.

[3] "List of Registered Additives." U.S. Environmental Protection Agency. March 3, 2010.

Table 2-3. Registered Gasoline Additives

Company Name	Additive Name
Brenntag West, Inc.	Methanol
Calwis Company, Inc.	Methanol (Calwis)
Quaternion Chemical Industries, Inc.	Methanol (Quaternion)
Range Fuels Soperton Plant LLC	Cellulosic Methanol Methanol
Valspar Corporation	SA1003 Gas-Line Anti-Freeze Methanol

have to go through the registration process with the EPA. Methanol waivers also require a cosolvent to offset the adverse effects of methanol, namely the negative volatility and the materials compatibility issues. The cosolvents are required to ensure that methanol is "substantially similar" to the certification fuel[4] that the EPA uses in its testing. Although not stated on EPA's website, it is anticipated that the methanol waivers apply only to blends with unleaded gasoline (i.e. RBOB) and not to ethanol gasoline blends.

Methanol can also be blended into unleaded gasoline that will meet the EPA's substantially similar rule for gasoline-oxygenate blends.[5] According to ASTM D4814 a fuel is substantially similar if the following criteria relative to methanol are met (see standard for full requirements):

1. Up to 0.3 volume percent methanol
2. Up to 2.75 volume percent methanol with an equal volume of butanol, or higher molecular weight alcohol

Under the federal **Clean Air Act Amendments** of 1990, severe and extreme ozone nonattainment areas were required to use **reformulated fuels** and areas of nonattainment could opt to require reformulated fuels. In response, states imposed requirements to comply with federal regulations and lower exhaust and evaporative emissions from automotive vehicles using reformulated fuels. Apart from the legal requirements – which vary slightly between states – reformulated fuels should meet the minimum performance requirements of the ASTM standard D 4814 (Standard Specification for Automotive Spark-Ignition Fuel). Many states have incorporated the ASTM standard test procedure into their laws related to reformulated gasoline: 37 states incorporated ASTM D4814, 23 states incorporated ASTM D 4806 for ethanol blending, and 17 states have incorporated ASTM D 5798 for high level blends of ethanol (i.e., E85). It is important to note that there is no federal requirement that ASTM standards be adopted for reformulated gasoline, but that states have opted to incorporate these standards as minimum requirements as part of their compliance with federal legislation. Based on TIAX's research, an ASTM standard would likely have to be developed for low level blends of methanol with gasoline or as part of a mixed ethanol-methanol oxygenate.

---

[4] The certification fuel is unleaded gasoline that must possess, at the time of manufacture, physical and chemical characteristics of ASTM Standard D4814-10 for at least one of the seasonal and geographical volatility classes specified in the standard.

[5] ASTM D4814-10, "Standard Specification for Automotive Spark-Ignition Engine Fuel"

Apart from reformulated gasoline requirements, the formulation of conventional gasoline has improved significantly to reduce evaporative emissions and tailpipe emissions. These improvements include limits on volatility (as measured by Reid Vapor Pressure, RVP) and reductions in sulfur content in the fuel.

The **California Reformulated Gasoline Regulations**[6] explicitly prohibit **oxygenates** other than ethanol or MTBE[7] as of December 31, 2003 in Sections 2262.6(c)(1). Methanol is listed as the first "covered oxygenate" in Section 2262.6(c)(4). Section 2262.6(c)(2) prohibits the use of methanol – and 10 other alcohols and ethers – as an oxygenate without conducting a multimedia evaluation[8] of use of the oxygenate in California. There are provisions in Section 2266 for certified gasoline formulations resulting in equivalent emission reductions based on motor vehicle testing; however, there is no exception to the prohibited oxygenated mentioned in Section 2262.6. TIAX contacted California Air Resources Board (CARB) staff and confirmed that in order to blend methanol into CARBOB that it would have to undergo a multimedia evaluation, despite previous use of methanol as a neat fuel in California and the federal waiver on record.

The EPA and California developed the Complex Model and the Predictive Model, respectively, to determine whether gasoline complies with RFG and anti-dumping emissions standards. The EPA Complex Model determines compliance with emissions reduction standards for toxic air pollutants (TAP), volatile organic compounds (VOC), and NOx. It also quantifies the effects of oxygen, benzene, aromatics, olefins, sulfur, and RVP on emissions and determines the percent of fuel evaporated at 200 and 300 °F. The California Predictive Model consists of a number of sub-models which relate gasoline properties to the exhaust emissions and evaporative emissions changes which are the result of gasoline use in a motor vehicle. The model consists of twenty-one separate exhaust sub-models for seven pollutants – NOx, hydrocarbons (HC), carbon monoxide (CO), benzene, 1,3-butadiene, formaldehyde (HCHO), and acetaldehyde. There are also six sub-models for evaporative emissions – 3 for HC and 3 for benzene.

In addition to the ASTM standards and the multi-media impact evaluation (California-specific), low level methanol blends in reformulated gasoline markets would also have to demonstrate compliance using both the Complex Model and the Predictive Model. Compliance with the respective models would require emissions testing on vehicles using the low level blended fuel and subsequent model modifications.

[6] Title 13, California Code of Regulations, Sections 2250-2273.5, The California Reformulated Gasoline Regulations, California Air Resources Board, effective August 29, 2008.

[7] The use of MTBE in neat form was banned as of December 31, 2003 in California.

[8] A multimedia evaluation provides information on "engine performance and emissions requirements but also with consideration of health and environmental criteria involving air emissions and associated health risk, ozone formation potential, hazardous waste generation and management and surface and groundwater contamination resulting form production, distribution, and use." Taken from *Guidance Document and Recommendations on the Types of Scientific Information Submitted by Applicants for California Fuels Environmental Multimedia Evaluations,* Cal/EPA, June 2008, UCRL-AR-219766

2.2 High Level Blend Strategy

Regulations and Standards

If methanol is used as a neat fuel in heavy-duty applications, then it would need to meet the stringent **2010 Model Year** standards for oxides of nitrogen (NO_x) and particulate matter (PM). TIAX is unaware of any engines using methanol in a heavy-duty application that have demonstrated compliance with these requirements; however, we believe that methanol could achieve these standards with tailored engine design, similar to natural gas engines e.g., using a stoichiometric engine with a three way catalyst.

The California Air Resources Board manages both the **Low-Emission Vehicle (LEV) Program** the **Zero Emission Vehicle (ZEV) Program**[9] with the objectives of reducing and eventually eliminating tailpipe emissions from mobile sources. At the federal level, the EPA manages the Tier 2 Vehicle and Gasoline Sulfur Program, which is similar to the LEV program in California. The LEV and Tier 2 standards include vehicle and evaporative emission controls. If high level blends of methanol are used, they will have to meet LEV-II and Tier 2 requirements. See Section 3.2 for more discussion of criteria pollutant emissions.

Looking forward, methanol in the light-duty sector may see a boost on the vehicle side if Congress passes the **Open Fuel Standard Act**. The act was introduced in Congress in July 2008 to increase production of flexible fuel vehicles in the U.S. Under the act's provisions, automakers would be required to ensure that starting in 2012, at least 50 percent of new vehicles powered by an internal combustion engine be FFVs warranted to operate on gasoline, ethanol, and methanol, or be warranted to operate on biodiesel. By 2015, at least 80 percent of vehicles must meet this requirement. This bill has not yet been passed, but its successful signing into law would potentially increase the availability of vehicles capable of using methanol. The Act is particularly important for methanol because the FFVs sold today are only compatible with blends of ethanol and gasoline.

2.3 Issue(s) Affecting Both Strategies

Regulations and Standards

The Energy Independence and Security Act of 2007 set target volumes for national biofuel production through the **Renewable Fuel Standard**. These targets affect demand for alternative fuels by mandating specific volumes of cellulosic biofuel, biomass-based diesel, advanced biofuel, and other renewable fuels through 2022. Methanol will be influenced by this legislation in two key ways:

1) Cellulosic sources such as wood, forest trimmings, paper production wastes, and corn stover can be gasified to produce methanol. While methanol is currently predominantly produced from natural gas, production from renewable sources would qualify it to meet RFS targets (see Figure 2-1).

[9] http://www.arb.ca.gov/msprog/zevprog/zevprog.htm

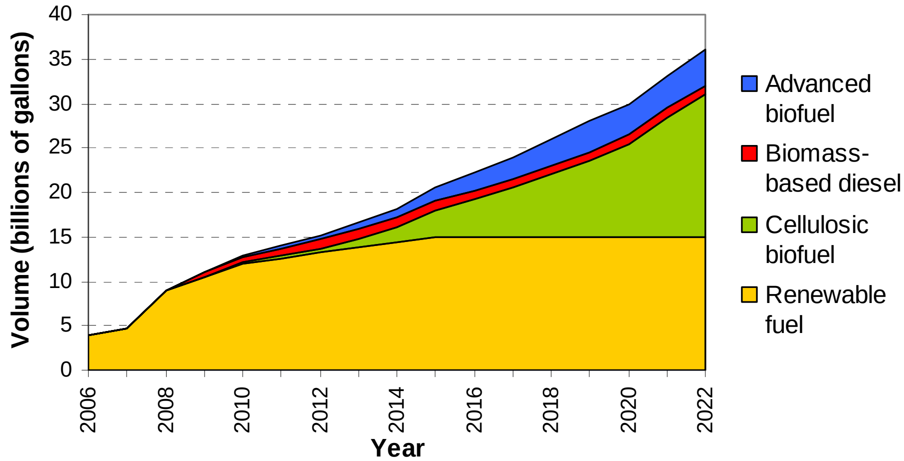

Figure 2-1. RFS2 Targets for Biofuel Production

2) Methanol is used in the transesterification process to produce biodiesel. Increased volumes of biomass-based diesel mandated in the RFS will require corresponding increases in alcohol reagents.

In California, the **Low Carbon Fuel Standard** was formalized by Assembly Bill 32 and established goals to reduce the carbon intensity of transportation fuels by 10 percent on a life-cycle basis by 2020. Similar legislation is being considered in Washington, Oregon, and in the Northeast States. Although there is no comparable legislation at the federal level, the standard in California and the progress in other states suggest that federal legislation may be considered in the near term. Depending on whether it is produced from renewable feedstocks, methanol has the potential to offer life-cycle reductions in carbon emissions, making it a compliance option under current and future carbon regulations.

Incentives

There are many financial incentives for alternative fuels at the federal level – the Alternative Fuels & Advanced Vehicles Data Center[10] lists more than 20 incentives for alternative transportation fuels. Methanol qualifies for only the three (3) of those federal incentives (listed in Table 2-4 below).

Table 2-4. Federal incentives for Methanol

Incentive/Credit	Value	Notes
Qualified Alt Fuel Motor Vehicle Tax Credit	LD: < $4,000 HD: < $32,000	No qualified methanol vehicles listed; expires Dec 31, 2010
Alcohol Fuel Mixture Credit	$0.60/gallon	Expired Dec 31, 2009
Cellulosic Biofuel Producer Credit	$0.41/gallon	Expires Dec 31, 2012

[10] Alternative Fuels & Advanced Vehicles Data Center, hosted by EERE/DOE; http://www.afdc.energy.gov/afdc/laws/fed_summary

3. Market Economic Issues

The methanol fuel market, similar to other alternative fuel markets, is primarily driven by the price of the fuel. The other market drivers include petroleum displacement, emission reductions, vehicle availability and infrastructure readiness, and consumer perception and acceptance.

3.1 Pricing Constraints

The distinction between low and high level blends of methanol is strongest when considering market conditions. Low level blends can be considered a displacement strategy for gasoline blendstock or ethanol on a volume basis. High level blends, however, are a displacement strategy for gasoline or diesel on an energy basis. The difference between displacing volume and energy using methanol is significant. To displace gasoline blendstock or ethanol on a volume basis, producers need only price methanol below the delivered cost of RBOB or ethanol (both about $2.00 per gallon average over the past 12 months).

In the case of displacing gasoline or diesel, producers must price methanol at the pump to be competitive on an energy basis, which includes the bundled costs of production, delivery, fueling stations, etc. The 12-month U.S. average pump price for gasoline and diesel are about $2.62 and $2.70 respectively. On an energy equivalent basis, methanol would require a (maximum) pump price including taxes of $1.30 and $1.20 as a neat fuel (M100) to compete with gasoline and diesel, respectively. In light-duty applications, methanol can also be used as M85 (85 percent methanol and 15 percent gasoline). In this case, M85 would need to be priced around $1.50 at the pump to compete with gasoline. Clearly, the price ceiling is much lower in the high level blend scenario than in the low level blend scenario.

We estimate the pump price of M85 to be about $1.66 in California, based on a build up including the cost elements listed in Table 3-1. This pump price is equivalent to about $2.90 on an energy equivalent basis with gasoline. This is about the same as the price for regular unleaded gasoline of $2.93. With a higher octane rating, M85 can also compete with premium unleaded gasoline, which is priced at $3.15 in California. M70 (70% by volume methanol and 30% by volume gasoline) could also be marketed. Using the same assumptions in Table 3-1, the pump price of M70 is $1.83 per gallon or $2.82 on an energy equivalent basis.

3.2 Other Market Drivers

Petroleum Displacement

In 2008, the U.S. consumed approximately 132 billion gallons of gasoline and 59 billion gallons of diesel fuel.[11] For fuel diversification and energy security purposes, the displacement of a fraction of the current petroleum consumption is a potentially significant driver.

---

[11] "Prime Supplier Sales Volumes." Energy Information Administration. http://tonto.eia.doe.gov/dnav/pet/pet_cons_prim_dcu_nus_a.htm. March 2010.

Table 3-1. Estimated Pump Price of M85

Cost/Price Element	Cost	Comments
Methanol – wholesale price	$0.95	13 month average (May 09 – May 10), from Methanex website
Gasoline – wholesale price	$1.95	13 month average (May 09 – May 10), from NYMEX RBOB
Bulk fuel transport	$0.05	Estimated based on EPA RFS documentation
Bulk fuel storage terminal	$0.02	Estimated based on EPA RFS documentation
M85 whole sale price	$1.15	
Truck transport	$0.07	
Federal excise tax	$0.093	http://www.energyalmanac.ca.gov/transportation/fuel_tax_rates.html
California excise tax + Underground tank fee	$0.11	http://www.energyalmanac.ca.gov/transportation/fuel_tax_rates.html
Station operating cost	$0.05	Assumes 4 M85 dispensers; calculated by TIAX
Capital recovery	$0.05	Calculated by TIAX
Operator profit	$0.02	Estimated by TIAX based on average distribution margins
CA sales tax	8.25%	http://www.energyalmanac.ca.gov/transportation/taxes.html
Retail M85 pump price	$1.662	
Energy equivalent price	**$2.899**	M85 Ratio 1.74 (RBOB 113,300 Btu/gal, methanol 56,560 Btu/gal)
CA gasoline pump prices		
Regular unleaded	**$2.93**	
Premium unleaded	**$3.15**	

In a low level blend strategy, methanol can displace petroleum in the gasoline markets that are not currently using ethanol, which is dwindling as the RFS requirements increase (e.g. in 2009 10.6 billion gallons were blended in gasoline; total consumption of gasoline was 138 billion gallons for an average ethanol blend of 7.7 percent--near the current limit of 10 percent). The barrier for this displacement potential, however, is that refiners are required to meet the RFS requirements, and current projections for ethanol use generally assume that ethanol will be blended into the entire gasoline market and then used either for blends greater than 10 percent or as E85 in FFVs. If methanol moves into the RFS market, then it will either need to be derived from a renewable resource (thus meeting the RFS requirements) or ethanol use will have to be increased in other areas/markets (e.g., increasing the blend in other places to E15).

Methanol in reformulated gasoline markets would more likely displace ethanol than gasoline. Ethanol is currently blended into RBOB up to 10 percent by volume as an oxygenate. Drivers for ethanol as an additive to gasoline include the fuel excise tax credit for blenders and the Renewable Fuel Standard. Ethanol also helps the refiners meet the RFG regulations. Renewable methanol could have a play in this market, however, if methanol from natural gas or coal is used to displace ethanol, then there would need to be a sizeable increase in ethanol demand in other sectors to maintain compliance with the RFS. In other words, the petroleum displacement potential for methanol in a low level blend with reformulated gasoline is dependent on a renewable feedstock.

There is potential for methanol to replace gasoline as a denaturant in ethanol. Gasoline is currently used as a denaturant in quantities of about 1-2 percent by volume of ethanol (with current ethanol blending limits of 10 percent a 1 percent methanol addition would be about 130 million gallons per year). In areas with oxygenated blendstocks, this would likely require a revised formulation and a new ASTM standard.[12] In areas without ethanol gasoline blends, it is possible that splash blends of methanol could be used. That said, ethanol is currently blended into most of the gasoline sold in the United States, so the issue of displacing ethanol rather than petroleum comes into play.

If methanol is to displace petroleum without causing knock-on effects like those mentioned above, then it would have to be in a high level blend (including as a neat fuel) scenario. The recent discoveries of vast natural gas supplies and improved extraction techniques, the petroleum displacement potential of methanol in a high level blend is good, in principle. However, this potential is highly dependent on the price of domestic natural gas. Natural gas providers will seek the highest value for their commodity. In addition to being a feedstock for methanol, natural gas can be used as a transportation fuel or in the power sector, among others.

Ultimately, petroleum displacement as a market driver for methanol has potential, but is dependent on other market considerations.

Emission Reductions

Methanol was originally pursued as part of an air quality strategy in California during the 1980s and 1990s to reduce tailpipe emissions of hydrocarbons and NO_x i.e., precursors to photochemical ozone formation. Today, however, the emission reduction potential is limited based on improvements in gasoline formulation and vehicle emission technologies over the last 20 years. There is marginal to no emission reduction potential for methanol in a low level blend strategy. In a high-level blend for either light-duty or heavy-duty vehicles, the evolution of criteria pollutant evaporative and tailpipe emission regulations (e.g., LEV-II in California and Tier 2 at the federal level) have drastically reduced the emissions advantage(s) of methanol.

Table 3-2. Light-duty and Heavy-duty Vehicle Tailpipe Emission Standards

<table>
<tr><th></th><th>Agency & Program</th><th>NO_x</th><th>ROG</th><th>CO</th><th>PM</th><th>HCHO</th></tr>
<tr><td colspan="2"></td><td colspan="5">g/mi</td></tr>
<tr><td rowspan="3">Light-duty</td><td>ARB - LEV II</td><td rowspan="2">0.07</td><td rowspan="2">0.09</td><td rowspan="2">4.20</td><td rowspan="2">0.01</td><td rowspan="2">0.018</td></tr>
<tr><td>EPA - Tier 2, bin 5</td></tr>
<tr><td>ARB – SULEV</td><td>0.02</td><td>0.01</td><td>1.0</td><td>0.01</td><td>0.004</td></tr>
<tr><td colspan="2"></td><td colspan="5">g/bhp-hr</td></tr>
<tr><td rowspan="2">Heavy-duty</td><td>ARB</td><td rowspan="2">0.20</td><td rowspan="2">0.14</td><td rowspan="2">14.4</td><td rowspan="2">0.01</td><td>0.01</td></tr>
<tr><td>EPA</td><td></td></tr>
</table>

[12] ASTM D4806-10, "Standard Specification for Denatured Fuel Ethanol for Blending with Gasolines for Use as Automotive Spark-Ignition Engine Fuel," currently prohibits the use of methanol as a denaturant.

The other market driver for emissions reductions is climate change i.e., GHG emissions as accounted for on a lifecycle basis. Methanol may reduce GHG emissions over gasoline and diesel (see Table 3-3). Methanol from renewable sources (e.g., poplar trees) is the most viable production pathway to comply with the goals of RFS2 and the LCFS in California, for instance. However, methanol from natural gas is the most common pathway in the United States.

Table 3-3. Lifecycle Carbon Intensity Values, reported as Well-to-Wheels and Indirect Land Use Change Effects

Fuel	WTW (g/MJ_{fuel})	ILUC (g/MJ_{fuel})
CARBOB	95.86	n/a
Ethanol (corn) [a]	67.50	30
California CNG	67.70	n/a
Electricity (California average) [b]	124.10	n/a
ULSD	94.71	n/a
Biodiesel (soy)	21.25	62
LNG [c]	72.38 – 93.37	n/a
Methanol (NG) [d]	*87.72*	*n/a*
Methanol (coal) [d]	*190.31*	*n/a*
Methanol (coal, with CCS) [d]	*89.32*	*n/a*
Methanol (renewable) [d]	*5.13*	*unknown*

Values taken from Tables 6 and 7 in the CA LCFS unless otherwise noted.
[a] average of the 1) Midwest average and 2) California average
[b] note that one must accommodate for the higher energy economy ratios (EERs) of electric vehicles compared to ICE vehicles
[c] range of values shown for 5 LNG pathways
[d] reported in TIAX LLC, "Full Fuel Cycle Assessment Well to Tank Energy Inputs, Emissions, and Water Impacts", Report for CEC, Feb 2007

In a low level blend scenario, methanol faces an interesting barrier in the near term: In California, methanol (from NG) offers a small GHG benefit over corn ethanol, due to the indirect land use change (ILUC) attributed to corn ethanol. However, the displacement of corn ethanol would have drastic impacts on compliance with the federal RFS. In light of this conflict between the federal standard and the LCFS in California – which is likely to be adopted in a similar fashion in other states – the GHG emission reduction potential of methanol in a low level blend strategy is low unless it is derived from a renewable resource.

In a high level blend scenario, methanol from renewable feedstocks could play a role in a long-term strategy. In the interim or as part of a mid-term strategy, methanol from natural gas could play a marginal role in meeting GHG emission reduction targets.

Lifecycle Costs

The price of methanol will vary considerably, as mentioned previously, in a low versus high level blend strategy. In a low level blend, methanol would displace ethanol, RBOB, or gasoline on a volume basis. In a high level blend, methanol would displace gasoline or diesel on an energy basis. The lifecycle costs of methanol are a function of 1) the price of the fuel and 2) the incremental cost of vehicles.

Methanol Feedstocks

The potential feedstocks for methanol production include a) coal, b) natural gas, and c) renewable sources e.g., biomass.

a. In the long-term, methanol production will have to shift from a fossil fuel feedstock towards a **renewable resource** if it is to have a role in a GHG reduction targets. Several companies have already or plan to manufacture methanol from renewable resources, including: BioMCN is making methanol from glycerin; Range Fuels is opening a cellulosic methanol plant; and, Carbon Recycling International is building a CO_2-based production plant in Iceland. Until there is demand for methanol from renewable resources on a larger scale, methanol production from renewable resources will continue to be expensive. It is worth noting that there is a volume limitation for renewable fuels based on available biomass resources, as is the case with any biomass-based alternative fuel (e.g., ethanol).

b. **Natural gas** is the most common feedstock for methanol globally. Recent improvements in extraction technology have substantially increased the reserves for natural gas in the United States (and in other countries as well), the discovery of so-called shale gas. The recent increase in the reserves of natural gas is a compelling driver for methanol production to be used as a transportation fuel. However, as a commodity, natural gas will have a myriad of markets that will affect its price, most notably in the energy and transportation sectors. Within the transportation sector itself, methanol production will have to compete with the direct use of natural gas as an alternative fuel.

c. In the transportation sector, we do not consider methanol derived from **coal** as a viable strategy because of the high GHG emissions associated with this pathway. If coupled with carbon capture and sequestration (CCS), coal as a feedstock is still unlikely to be a viable strategy based on its GHG emissions (see Table 3-3) and the costs of CCS.

Incremental vehicle costs

The other main driver for lifecycle costs is the incremental cost of vehicles. In the light-duty sector, E85 FFVs have incremental costs in the range of $50-100. In the case of methanol, however, we estimate that the cost may be as high as $500 per vehicle. The difference in price is based on ethanol being much closer to gasoline relative to materials compatibility than methanol. In the heavy-duty sector, incremental costs are upwards of $20,000. [13]

[13] "A Summary of Methanol, Ethanol, CNG, LNG, LPG, Hydrogen, Dimethyl Ether, Biodiesel, Fischer Tropsch, Electric, Hybrid-Electric, and Fuel Cell Technologies." Prepared by ICF Incorporated and Arcadis Geraghty & Miller for Environmental Protection Agency. September 1998.

Lifecycle Cost Savings Potential

We only consider the lifecycle cost savings potential for high level blends, as shown in Table 3-4. The cost savings are reported as costs to the consumer. Methanol may offer cost savings over conventional fuels, depending on a) the pump price of the fuel and b) the incremental cost of the vehicle. Although upfront vehicle costs will be initially higher for methanol vehicles than conventional vehicles, these costs may be outweighed by the cost savings of the fuel over their operating lifetimes for both light- and heavy-duty vehicles. The estimated life-cycle costs are based on a $0.85-$0.95 per gallon delivered cost of methanol (see Table 3-1 for pump price).

Table 3-4. ICEV Lifecycle Cost Comparison ($2010)[14,15,16,17,18]

	Light-duty			Heavy-duty		
	Gasoline	M-85		Diesel	M100	
Lifetime	10			10		
VMT (miles/yr)	12000			66000		
		low	high		low	high
Fuel economy (mpg_{fuel})	27.5	15.8	15.8	5.1	2.4	2.4
Pump price	$3.00	$1.47	$1.65	$3.20	$1.28	$1.28
Incremental vehicle cost	—	—	$800	—	$11,400	$22,800[19]
Total lifecycle cost	**$13,091**	**$11,832**	**$12,947**	**$414,118**	**$393,503**	**$409,386**
Savings		**$1,259**	**$144**		**$20,615**	**$4,731**

The lifecycle cost savings that we estimate in light-duty applications is about $10-100 per year over an estimated 10 year lifetime. We do not consider these cost savings to be sufficiently attractive enough to offset other negative attributes such as a (slightly) higher vehicle price and limited fueling infrastructure. To make the lifecycle savings more attractive, the M85 pump price would have to drop considerably. This would require, for instance, more efficient delivery using pipelines or higher efficiency methanol vehicles (compared to gasoline). Gasoline is currently sold with ethanol blended up to 10 percent by volume. Even at elevated levels of ethanol use, there has not been a concerted effort to transition toward dedicated ethanol pipelines. However, reducing bulk fuel transportation has only a minor affect on methanol plump price and is much less than the methanol spread shown in Table 3-4. Higher efficiency methanol engines could be effective, but substantial improvements are also being made to gasoline technologies.

---

14 Dolan, G. "Methanol Transportation Fuels: From U.S. to China." IAGS Briefing to U.S. House of Representatives. April 16, 2008.

15 "Fuel Tax Rates." International Fuel Tax Association, Inc. http://www.iftach.org. January 2010.

16 Jackson, M.D., E.J. Geiger, C.A. Sullivan, J.Wiens. "Field Demonstration of Ford 6.6L MX Methanol Engine at Arrowhead Drinking Water Company." SAE Technical Paper 922270. October 1992.

17 "Motor Fuel Taxes." American Petroleum Institute. http://www.api.org/statistics/fueltaxes. January 2010.

18 Wuebben, P., S. Unnasch, V. Pellegrin, D. Quigg, B. Urban. "Transit Bus Operation with a DDC 6V-92TAC Engine Operating on Ignition-Improved Methanol." SAE Technical Paper 902161. October 1990.

19 The incremental cost of heavy-duty methanol vehicles may be over-estimated. As a result of stringent 2010 standards for heavy-duty engines, additional costs to control emissions will be incurred e.g., particulate traps and selective catalytic reduction (SCR) technologies.

For heavy-duty vehicles, the lifecycle cost savings are $470-$2100 per year over an estimated 10 year lifetime. We believe that the savings are probably closer to the lower end of that estimate. Although modest, we do think that these savings would be attractive enough in some applications to warrant introduction of M100, especially if the first costs of heavy-duty methanol engines/vehicles can be reduced.

On the light-duty vehicle side, ethanol compatible FFVs are already produced at approximately price parity. We assume that the price for methanol FFVs is slightly higher as indicated in Section 4.

Vehicle Availability

Low level blends of methanol (up to 5 percent by volume with cosolvents) should be compatible with the existing fleet of vehicles. The remaining discussion pertains to vehicles for high level blends of methanol.

The technology for methanol used in ICEVs is very similar to the technology used for gasoline vehicles and is well understand. While vehicles could technically be made more efficient and available, the market conditions are a challenge for methanol i.e., the price of gasoline is low, government policies and incentives (e.g., fuel excise tax credits, RFS) generally favor other alternative fuels. As such, it may be difficult to demonstrate to automobile manufacturers that there is a business case to warrant the extra cost, albeit small on a per vehicle basis, associated with the manufacture of M85 compatible FFVs.

Infrastructure Readiness

Technical challenges to develop methanol distribution, storage, and dispensing infrastructure are primarily related to materials compatibility issues, as discussed previously, and are well understood. The challenge of introducing methanol involves establishing and expanding a network of distribution infrastructure and the availability of equipment compatible with methanol, especially in low production volumes. Low level methanol-cosolvent-unleaded gasoline blends can be accommodated by the existing infrastructure. The discussion below pertains to high level blends of methanol, including its use as a neat fuel.

In the late 1980s, over 100 public and private stations with methanol dispensing capability were built to support methanol vehicles in California.[20] Many of these vehicles were operated in fleets for the state's methanol program. Demonstration projects in this program indicated that the limited number of fueling stations hindered the acceptance of methanol vehicles by end users. Furthermore, surveys demonstrated that the most frustrating part of the fleet program was not the technology itself but rather non-methanol related issues.[21] For example, users experienced many problems with the new cardlock system used to purchase the fuel. The evaluation report for California's Methanol Program concluded that "the result [was] a technically sound system that […] frustrated drivers trying to get fuel, generating an understandably negative response to the

---

[20] Ward PF and Teague JM (California Energy Commission), *Fifteen Years of Fuel Methanol Distribution*, 1996. http://www.energy.ca.gov/papers/CEC-999-1996-017.PDF

[21] "California's Methanol Program Evaluation Report, Volume II: Technical Analyses." Prepared by Acurex Environmental for California Energy Commission. June 1987.

vehicles and program overall."[22] Additional recommendations based on California's demonstration efforts were that a greater number of more reliable stations needed to be added to the fueling network and that a transition strategy was needed to make methanol acceptable to the general public.[23]

Methanol fueling stations were gradually phased out in the 1990s due to insufficient throughput and lack of interest by station operators. Reformulated gasoline could achieve tighter emissions standards that previously only methanol could meet. This provided the strategy for petroleum derived fuels to maintain their market share. Without the needed infrastructure to support methanol consumption, coupled with the availability of reformulated gasoline, the use and purchase of methanol vehicles declined as well, eliminating the market share and adoption of methanol fuel to its current state.

In order for methanol to be a viable transportation option in ICEVs , a targeted, strategic approach to infrastructure availability is needed. The fleet approach taken by California's Methanol Program was successful in putting methanol vehicles on the road and bringing fuel consumption to a peak of over 12 million gallons in 1993.[24] However, the fleet approach is not sustainable because fleets opt to buy the cheapest cars available. Apart from the challenges of pricing the fuel, a sustainable market for methanol in a high level blend strategy will require the simultaneous and geographically matched deployment of infrastructure and vehicles, along with long-term plans for capturing station owner interest.

Consumer Perception

Consumer awareness and perception of methanol as an alternative fuel is not a significant barrier, particularly outside of California. Although methanol received strong support from agencies such as the California Energy Commission and the California Air Resources Board as an air quality improvement strategy in the 1980s and 90s, cleaner reformulation of gasoline eliminated that advantage of methanol. At the same time, the addition of MTBE – which is produced using methanol – to gasoline provided another, more profitable, market for methanol. The subsequent bans on MTBE over health and environmental concerns have eroded support for methanol use as a transportation fuel amongst California policy makers, and perhaps less so at some federal regulatory agencies. However, general consumer perception towards methanol is not a barrier towards greater implementation.

By and large, transportation fuels, including gasoline and methanol, can be dangerous. The health and environmental risks of transportation fuel use are mitigated by developing safe handling guidelines, storage requirements, proper warning labels for consumers, etc. From a fire safety standpoint, methanol is safer than gasoline; methanol burns cooler, releasing one-eighth the heat of gasoline fires.[25] On the other hand, pure methanol burns with low luminosity, which

---

[22] *Ibid.*

[23] "California's Methanol Program Evaluation Report, Volume II: Technical Analyses." Prepared by Acurex Environmental for California Energy Commission. June 1987.

[24] Ward PF and Teague JM (California Energy Commission), *Fifteen Years of Fuel Methanol Distribution*, 1996. http://www.energy.ca.gov/papers/CEC-999-1996-017.PDF

[25] "A Summary of Methanol, Ethanol, CNG, LNG, LPG, Hydrogen, Dimethyl Ether, Biodiesel, Fischer Tropsch, Electric, Hybrid-Electric, and Fuel Cell Technologies." Prepared by ICF Incorporated and Arcadis Geraghty & Miller for Environmental Protection Agency. September 1998.

was one of the reasons methanol for vehicles was blended with 15 percent gasoline to create the M85 blend. Methanol is slightly more toxic than gasoline based on its fatal ingestion range (as measured in mL) but it is neither mutagenic nor carcinogenic. From an environmental standpoint, methanol is readily biodegradable with a half-life in groundwater of 1-7 days (compared to 10-730 days for benzene, a component of gasoline).

As a low level blend strategy, the methanol industry may capitalize on the current debate regarding the use of corn ethanol as a transportation fuel – the so-called food versus fuel debate. The primary environmental concern is the indirect land use change attributable to the production of biofuels from dedicated crops such as corn or sugarcane. Both the California Air Resources Board and the Environmental Protection Agency have opted to include the GHG emissions attributable to biofuels for these so-called indirect land use change (ILUC) effects in their rulemaking for the LCFS and RFS, respectively. Climate change legislation and incentive will continue to be a significant driver (and barrier) for transportation fuels. The negative association of biofuels from food crops may further improve the position of methanol in the alternative fuels marketplace.

4. Review of Materials Compatibility with Methanol

This section is divided into two parts:

1. Review of Existing Methanol Vehicle Materials Compatibility Issues
2. Review Materials Testing Literature – TIAX conducted a literature review of materials testing for methanol fuel blends.

4.1 Review of Existing Methanol Materials Compatibility Issues

The automakers developed flexible fueled vehicles in the late 80's to help with the transition from gasoline to alcohol fuels. The vehicles were first designed by Ford for methanol fuel blends—going from gasoline to M85 (a mixture of 15 percent by volume gasoline with methanol). Ford as well as General Motors and Chrysler sold these vehicles in California as part of the California Energy Commission's Methanol Fuel Program. The CEC program also included a network of methanol fuel stations at branded and independent stations. This program continued into the mid 90's and tapered off as reformulated gasoline with MTBE was shown to have substantial emissions benefits and vehicle technologies were designed to make use of the favorable reformulated gasoline properties.

Ford adapted their FFV technology to their 1996 Taurus. Two versions of this vehicle were developed—one for methanol and one for ethanol. As a result of reformulated gasoline and other market forces, Ford announced at the XII International Symposium on Alcohol Fuels (ISAF) in 1998 that their flexible fuel vehicles would only be compatible with ethanol and would no longer be capable of using methanol fuel mixtures. Ford indicated at the time this saved them costs for more expensive fuel system components to handle the more corrosive methanol and also saved them costs of a more expensive catalyst aftertreatment system (the methanol version was certified to a lower emission standard than the ethanol version).

Material Compatibility with Alcohols

Methanol is more aggressive than ethanol relative to materials compatibility. Methanol is known, for example, to be very corrosive to aluminum whereas ethanol is not as corrosive. Automakers, therefore, have to pay more attention to the wetted fuel system components of methanol vehicles compared to ethanol and gasoline fueled vehicles. Also, the fuel dispensing materials need to be designed to handle the more corrosive methanol fuels.

The vehicle fuel system components that need modifications for material compatibility include fuel cap, fuel lines, fuel pump, fuel tank, and elastomers such as o-rings. There are no show stoppers to specifying that these components be compatible with methanol, it is more an issue with costs of materials and the volume of the components. For example, FFVs designed in the mid-1990s used two speed fuel pumps to meet the increased fuel delivery needed for the lower energy content of the alcohols. Methanol pumps where considerably more costly compared to ethanol pumps (ethanol pumps were 25 to 33 percent the costs of methanol pumps).

Ford in a supplement to their owner's manual provided a list of changes made to the gasoline Taurus for flexible fuel operation. Table 4-1 shows the changes made. "Alcohol fuel compatibility" was defined by Ford to mean that the component performs satisfactorily, is durable, and does not contaminate the fuel when tested in worst-case methanol-gasoline and ethanol-gasoline blends up to 85 percent alcohol. Ford also indicated in this owner's manual supplement that "the same special materials and procedures developed for the Taurus Methanol FFV are used in the Taurus Ethanol FFV."

Table 4-1. Ford Taurus FFV Component Changes[26]

Item Changed	Description
Spark Plug	Has a colder heat range and the wire electrode is wider for better heat transfer
Engine	Internal engine changes for "alcohol fuel compatibility"
Fuel Injectors	Higher fuel flow capacity, modified spray nozzle design and material changes for "alcohol fuel compatibility"
Engine Oil	Specifically designed for engines operated with methanol and ethanol fuels
Fuel Rail	Material changes are made for "alcohol fuel compatibility"
Fuel Pressure Regulator	Material changes are made for "alcohol fuel compatibility"
Engine Block Heater	Use to assist in cold start below -12 deg C
PCM processor	Calibration is utilized to optimize engine function for alcohol fuel operation
Wiring Harness	Wiring changes have been made to connect with the fuel sensor
Fuel Sensor	Determines the percentage of methanol in the fuel for methanol FFVs or percentage ethanol for ethanol FFVs
Fuel Supply and Return Lines	Material changes are made for "alcohol fuel compatibility"
Fuel Pump Assembly/Fuel Sending Unit	Fuel pump specifically designed for alcohol fuels. Stainless steel parts are used.
Vapor Control Valve	Control vapor flow to charcoal filter
Filler Tube	Improved coating is applied and anti-siphon screens installed
Fuel Filter	Material changes are made for "alcohol fuel compatibility"
Charcoal Canister Tray	Protective enclosure
Evaporative Emission System	Charcoal canister system enlarged and modified for additional alcohol fuel vapor capacity and higher vapor flow
Vapor (Rollover) Valves	Helps to increase fuel capacity and vapor flow. Material changes are made for "alcohol fuel compatibility"
Fuel Tank	A specially coated steel fuel tank is used for "alcohol fuel compatibility"

[26] Ford, "Taurus FFV Supplemental Owner Guide," 1998.

Ford tested all materials that came in contact with the alcohol fuel or fuel vapors. For the Taurus, they upgraded fuel lines and rails and used stainless steel or glass filled poly phenylene sulfide resin. Ford indicated for ethanol FFVs the conditions are less severe and that less costly materials give acceptable results. For elastomers like o-rings, Ford found that high fluorine content fluoroelastomers demonstrated compatibility with alcohol fuels. Material selection for fuel pumps, injectors, and fuel sensors is also very important to ensure durability.

Engine and Emissions Control System

Engine and emissions control systems require changes for alcohol fuels, including: wider bandwidth injectors, higher fuel pump delivery volume, alcohol sensor, and engine-emissions calibration. For a FFV that is calibrated to ethanol, methanol, and gasoline there are a number of compromises that are needed relative to vehicle performance, emissions performance, and recall mitigation. Most likely separate calibrations (as Ford did with the Taurus) would be required for ethanol and methanol and the automakers may bias the calibration to the marketplace where one fuel dominates, e.g. ethanol in the Midwest.

With the sophistication of today's emission control systems the current ethanol-gasoline FFVs do not require a fuel sensor, but can rely on the oxygen sensors in the emission control system. This may not be possible for a FFV that would have to operate on ethanol, methanol, and gasoline. Again, it may be necessary to identify what fuel is being used and then to switch to the appropriate engine calibrations. This could get complicated if the vehicle has to be designed to meet stringent emissions standards for any combinations of methanol, ethanol, and gasoline.

It is very likely that FFVs capable of methanol <u>and</u> ethanol operation would require a fuel sensor and this would add to the cost of the vehicle. Additional calibration costs would be required for methanol. These costs are not small and are in the range of $1 million per engine vehicle combination for gasoline vehicles and higher to cover a variety of alcohol-gasoline mixtures. These costs are amortized over the vehicle volumes sold.

Evaporation and After-treatment Systems

We believe that current ethanol FFVs are using gasoline like catalysts[27] to meet the tailpipe standards. In the past, methanol FFV catalysts required more precious metals and, therefore, were more costly. Also in the case of Ford's methanol FFV Taurus, it was designed to meet California's TLEV standard and the ethanol FFV was designed to meet federal standards. The methanol FFV included close-coupled, light-off catalyst as well as under floor catalysts. The ethanol version only included under floor catalysts[28].

The vapor pressure of ethanol-gasoline and methanol-gasoline blends peak at low blend levels. This increases the amount of fuel evaporation and requires additional changes to the evaporative control system. Methanol may require specifying different materials and this would increase costs. Newer vehicles do not recirculate as much fuel as the systems from the 1990s, so there is

---

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

[28] 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

less fuel temperature rise. This helps to lower evaporative emissions. Nevertheless, both alcohols require changes to the evaporative system that add costs compared to a gasoline vehicle.

Fuel permeation through hoses, o-rings, fuel tanks causes additional emissions that need to be controlled. In general these emissions are reasonably well controlled with ethanol FFVs due to proper material specification. Additional work is needed to determine the effect of permeation for methanol FFVs. Due to the more aggressive nature of methanol on materials additional costs may be necessary to ensure material compatibility with methanol.

Engine Design

Engine design changes may also be necessary to accommodate alcohol fuels. In the development of the 1996 FFV Taurus Ford found that preignition was a problem for methanol due to its low surface ignition temperature.[29] Hot spots in the combustion chamber would result in preignition with methanol (ethanol was much less prone to preignite due to its higher surface ignition temperature). Ford made substantial changes in the cylinder heads and also incorporated a colder heat range spark plug to eliminate preignition. These changes may have not been needed for an ethanol only FFV.

Another area that needed addressing was engine wear. Two areas needed to be addressed: cylinder bore/piston ring wear and valve seat wear. Since nearly twice the fuel flow is needed with methanol compared to gasoline, there is a tendency for bore washing. Coupling this to the solvent nature of the alcohols leads to abrasive bore/piston ring wear. Ford incorporated an improved iron containing less ferrite and a higher Brinell hardness for their FFV engines. They also specified a hard chrome top ring and heat treated cast iron second ring along with a unique synthetic oil blend. Relative to valve wear, Ford found that they did not need to change the gasoline valve, but did need to change the exhaust valve seat inserts for acceptable wear.

2010 FFV Models

A number of automakers are producing ethanol FFVs for model year 2010. Manufacturers include Chrysler, Ford, General Motors, Mercedes Benz, Mitsubishi, Nissan, and Toyota. Most of the models offered are light duty pickup trucks and SUVs. We checked the owner’s manual for the 2010 Chevrolet Tahoe/Suburban and the 2010 Ford F150. Both manufacturers indicate that E85 could be used for the FFV versions and that E85 should, at a minimum, meet ASTM Specification D5798. GM also added the following relative to methanol:

> **Notice: This vehicle was not designed for fuel that contains methanol. Do not use fuel containing methanol. It can corrode metal parts in the fuel system and also damage plastic and rubber parts. That damage would not be covered under the vehicle warranty.**

Ford’s warning was even more strongly worded:

> **Use of other fuels such as Fuel Methanol may cause powertrain damage, a loss of vehicle performance, and your warranty may be invalidated.**

---

[29] *Ibid.*

Although we did not check all the FFV owner's manuals, we believe similar warnings are provided by the other automakers.

Summary

Table 4-2 summarizes very rough estimates of the extra costs of manufacturing methanol FFVs compared to ethanol FFVs. A fuel sensor was included to cover the possible manufacturing of FFVs that could use methanol, ethanol, gasoline, or any combination of the fuels. If only a methanol FFV is manufactured then a sensor is probably not needed. Fuel system materials would need to be changed to handle the more corrosive methanol but these costs are estimated to be small. Fuel pump costs could be considerably higher due to material changes but also economies of scale if only these pumps are made for methanol FFVs and not incorporated in ethanol FFVs or more broadly in the automakers' gasoline products. Methanol catalysts are estimated to need more precious metals based on the experience in the 90's. Again, limited volume would also cost the manufactures more for the methanol catalyst. Finally, we estimate that the evaporative system would need some material changes for methanol. We believe these are minor and would not affect volume pricing of the components. Not included in these costs are the time and effort needed to calibrate the vehicle to meet performance and emissions standards. California PZEV standards are currently a challenge with ethanol and would be even more difficult with methanol.

Table 4-2. Estimate of Extra Cost of Methanol FFV Compared to Gasoline Vehicles

Component	Material Costs	Volume Costs	Total
Fuel Sensor			$100
Fuel System Materials	$50		$50
Fuel Pump	$20	$100	$120
Catalyst	$100	$100	$200
Evaporative System	$20		$20
		Total Estimated Costs	$490

It has been estimated that the extra cost of ethanol FFVs is about $100. This cost covers, we believe, the larger bandwidth injectors, larger fuel pump, and engine calibration. We believe that very few gasoline components have been changed to accommodate ethanol. The extra cost for ethanol FFVs is minor because they are not using a sensor, and they have the same catalyst (or have comparable catalyst costs) as gasoline. This is supported by two significant decisions: a) the OEMs do not charge a premium for their FFV models and b) domestic OEMs have committed to produce 50 percent of their vehicles as ethanol FFVs.[30]

The cost estimates shown in Table 4-2 for M85 FFVs assume that all the material and equipment changes are required. Lower costs are possible. Using M70, for example, might allow the E85 injectors and fuel pump to be used, since M70 and E85 have similar energy densities. Further, it

[30] Some of the OEMs FFV costs are being offset by the current incentives in the CAFE regulations. Nevertheless, we believe the incremental costs of the current ethanol FFVs are very small.

may be possible to reduce or eliminate any material compatibility issues with M70 compared to E85 with the use of cosolvents. The result would be a M70-E85 FFV with comparable costs provided no catalyst or evaporative changes are needed. Research and testing are needed to verify this possibility. Thus, depending on material compatibility, emissions, and grade of methanol marketed, the incremental costs of methanol FFVs compared to ethanol FFVs could be from $0 to $490 per vehicle.

4.2 Review of Materials Testing Literature

Materials compatibility testing of methanol fuel for vehicles dates back to the 1970s. Motivated by growing interest in adoption of methanol as a transportation fuel, various studies since that time have addressed the compatibility of methanol with metals and polymers in both laboratory tests and vehicle and infrastructure demonstrations. Testing has been conducted for select low and high level methanol blends, with few studies examining the entire blend range. In general, fundamental methanol compatibility issues with materials commonly used in vehicles and fueling infrastructure have been identified, but long term effects of use of methanol fuel remain to be seen.

The following section lists key studies related to materials compatibility testing of methanol and highlights major conclusions from these studies.

Abu-Isa, I.A. "Effects of Gasoline with Methanol and with Ethanol on Automotive Elastomers." SAE Paper 800786. June 1980.
Testing of the effects of methanol-gasoline blends on sixteen elastomers. Blends varied from 0 to 100 percent methanol, and elastomers were evaluated in terms of volume change, tensile strength, and elongation. Few elastomers were drastically affected by pure gasoline or pure methanol, but most elastomers were severely affected by blends of the two fuels.

Abu-Isa, I.A. "Elastomer-Gasoline Blends Interactions, Part I and Part II." Rubber Chemistry and Technology 56(1): 135-196. March-April 1983.
Testing of elastomer swell in methanol relative to gasoline. Methanol blends were neat methanol and 10 percent methanol with 90 percent gasoline, and elastomers tested were fluorocarbon, polyestere urethane, fluorosilicone, butadiene-acrylonitrile, polyacrylate, chlorosulfonated polyethylene, ethylene-propylene-diene terpolymer, and natural rubber. For four of these elastomers, swell effects of the 10 percent methanol blend were more significant than those of pure methanol and pure gasoline.

"Alcohols and Ethers–A Technical Assessment of Their Application as Fuels and Fuel Components," Second Edition. API Publication 4261. American Petroleum Institute. July 1998.
Summary of information from technical literature on producing and applying alcohols and ethers as fuels and fuel components. States that while "a wide variety of corrosion inhibitors have been screened, including polyamide, polyamine, dithiocarbamate, thiophosphate ester, organic acid, sulfide, and selenide types, as yet none have been found to be effective." Discusses considerations for fuel tank material for neat methanol compared to gasoline-methanol blends.

Bechtold, R.L, M.B. Goodman, T.A. Timbario. "Use of Methanol as a Transportation Fuel." Prepared by Alliance Technical Services Inc. for Methanol Institute. November 2007.
Summary of history, work to date, and considerations for use of methanol in transportation applications. Indicates that although millions of flex-fuel vehicles have been sold to date, it is still unknown exactly what material changes manufacturers have made to accommodate alcohol fuels. Raises concerns that results seen in materials compatibility tests may vary depending on age and shape of elastomers in actual use.

Bellucci, F., G. Faita, C.A. Farina, F. Olivani. "The Passivity of Ferritic (Fe-18% Cr) Stainless Steel in Methanolic Solutions." Journal of Applied Electrochemistry 11(6): 781. 1981.
Testing of active-passive behavior of ferritic (Fe-18% Cr) stainless steel in methanol as a function of chloride ion concentration, acidity, and water addition. Indicates that at high acidity, stainless steel will corrode in methanol.

Brossia, C.S., E. Gileadi, R.G. Kelly. "The Electrochemistry of Iron in Methanolic Solutions and Its Relation to Corrosion." Corrosion Science 37(9): 1455-1471. September 1995.
Testing of corrosion behavior of iron in methanol. Showed that inhibition of corrosion by water is primarily due to decreased proton mobility with increasing water content and preferential protonation of water over methanol.

"California Advisory Board on Air Quality and Fuels (AB 234): Economics Report (Volume IV)." P500-86-012A. Prepared by Acurex Corporation for California Energy Commission. June 1990.
Summary of expert testimony on the economics of alternative fuels, particularly methanol. In response to question regarding how much work has been done and remains to be done for elastomers in flex-fuel vehicles, Ford Motor Company indicated that "each different product requires new things to be checked, because, for instance, components are different than in the Crown Victoria."

"California's Methanol Program Evaluation Report, Volume II: Technical Analyses." Prepared by Acurex Corporation for California Energy Commission. June 1987.
Summary of California Energy Commission's demonstration experiences with methanol vehicles and fueling infrastructure. Describes component failures with methanol use in fueling stations and heavy-duty transit operation and changes made to components to address problems.

"The Corrosion of Metals in Methanol-Fueled IC Engines." Prepared by Pinnacle Research Institute, Inc. for California Energy Commission and U.S. Department of Energy. July 20, 1983.
Accelerated testing method using electrochemical techniques for corrosion rate on cast iron exposed to exhaust gas condensate of methanol-fueled vehicles. Determined that formation of high nitric acid concentration in condensate is the major cause of corrosion, and rate of corrosion is directly proportional to acidity of the condensate and is relatively invariant toward the methanol content of the condensate. Indicates that diffusion of condensate through the protective oil coating on the engine wall is greatly enhanced with methanol content—lubricating oil

developed for gasoline engines is ineffective in preventing corrosion and wear in methanol-fueled engines.

"A Discussion of M85 (85% Methanol) Fuel Specifications and Their Significance." SAE Cooperative Research Program. September 1991.
Summary of fuel system durability with M85 including: metallic, static, electrolytic corrosion; anodic dissolution; particulate contamination and wear; and elastomer swell. Suggests that while addition of water to methanol generally plays a passivating role in the corrosion of metals, in the presence of some contaminants, water addition enhances corrosion.

Dunn, J.R., H.A. Pfisterer. "Resistance of NBR-Based Fuel Hose Tube to Fuel-Alcohol Blends." SAE Paper 800856. June 1980.
Testing of physical properties of nitrile rubber after exposure to methanol fuels. Blends were 0, 2.75, and 20 percent methanol in ASTM Fuel C (50 percent iso-octane, 50 percent toluene).

Fanick, E.R., J.A. Russell, L.R. Smith, M. Ahuja. "Laboratory Evaluation of Safety-Related Additives for Neat Methanol." SAE Paper 902156. October 1990.
Testing of effects of various additives on improving methanol safety aspects, including fuel lubricity. Surface-active additives shown to reduce wear of metallic surfaces in methanol fuels.

Farina, C.A., G. Faita, F. Olivani. "Electrochemical Behavior of Iron in Methanol and Dimethylformamide Solutions." Corrosion Science 18: 465. 1978.
Testing of electrochemical behavior of pure iron in methanol solutions with varying water content and chloride ion concentration. Indicated that chloride ions increase metallic corrosion by activating metal surface.

"Gasoline/Methanol Mixtures for Materials Testing." SAE Cooperative Research Program. September 1990.
Specification of fuel blends for materials compatibility testing; test fuel recipes for polymer testing, metals testing; and decision tree for testing elastomers and plastics.

Ingamells, J.C., R.H. Lindquist. "Methanol as a Motor Fuel or a Gasoline Blending Component." Presented at Automotive Engineering Congress and Exposition, Detroit, MI. February 1975.
Laboratory and road testing of methanol in vehicle use. Detailed corrosion and degradation problems with lead, magnesium, aluminum, and some plastics. Identified major problem with methanol/gasoline blends in conventional fuel tank is corrosion of terneplate lining (75-90 percent lead, 10-25 percent tin) by methanol. Demonstrated ineffectiveness of nine classes of commercial corrosion inhibitors for methanol.

Keller, J.L., G.M. Nakaguchi, J.C. Ware. "Methanol Fuel Modification for Highway Vehicle Use—Final Report." HCP/W3683-18. Prepared by Union Oil Company of California for U.S. Department of Energy. July 1978.
Testing and identification of problems with methanol as a blending stock or replacement of gasoline, characterized by probability of occurrence and severity of consequences. Detailed test data provided on compatibility of neat methanol and blends with fuel distribution and engine systems: direct loosening in gasoline distribution system tanks, solvent effect of methanol on automobile paint finishes, fuel pump wear, compatibility of methanol and blends with metals,

compatibility of methanol and blends with non-metals, and effect of blends on carburetor detergency properties.

Liu, Z., S. Xu, B. Deng. "A Study of Methanol-Gasoline Corrosivity and its Anticorrosive Agent." In Proceedings of the Tenth International Symposium on Alcohol Fuels, Colorado Springs, CO, Volume 1: 96. November 7-10, 1993.
Testing of effects on metal corrosion of methanol-gasoline blends with and without four cosolvents. Blends were 3, 5, and 10 percent methanol, and metals were copper, cast iron, steel, and aluminum. Cosolvents were found to be effective in reducing the corrosive effects of methanol blends.

Marbach, H.W., Jr., E.A. Frame, E.C. Owens, D.W. Naegli. "Effects of Alcohol Fuels and Fully Formulated Lubricants on Engine Wear." SAE Paper 811199. October 1981.
Testing of engine wear by neat methanol and blend of 10 percent methanol and 90 percent gasoline. Indicated that engine wear is inversely related to engine oil temperature when methanol is used.

Methanol Safe Handling Manual. Prepared by Alliance Consulting International for Methanol Institute. Oct 2008.
Summary of general issues pertaining to materials selection for compatibility with methanol. Discusses basic effects of pure hydrous and anhydrous methanol on aluminum alloys, magnesium, platinum, copper alloys, zinc, steel, titanium alloys, and various polymers.

Nersasian, A. "The Volume Increase of Fuel Handling Rubbers in Gasoline/Alcohol Blends." SAE Paper 800789. June 1980.
Testing of swelling effects of polymers in methanol-gasoline blends. Blends ranged from 0 to 100 percent methanol, and polymers included fluorohydrocarbon, fluorosilicone, nitrile, epichlorohydrin homopolymer, and copolymer rubbers. Highly fluorinated fluorohydrocarbon rubbers showed best resistance to swelling.

Owens, E.C., H.W. Marbach, Jr., E.A. Frame, T.W. Ryan, III. "Effects of Alcohol Fuels on Engine Wear." SAE Paper 800857. June 1980.
Investigation of effects on engine wear and deposits by methanol fuel in spark-ignition engines. Indicated that at low temperature conditions, methanol reduces build-up of deposits but greatly increases engine wear rate. Report of experiments to identify wear mechanisms.

"Recommended Methods for Conducting Corrosion Tests in Gasoline/Methanol Fuel Mixtures." SAE Cooperative Research Program. June 1992.
Standard practices for methanol fuel corrosion tests: laboratory immersion corrosion test of metals; vibratory cavitation erosion-corrosion testing; preparation and use of stress-corrosion test specimens; and conducting and evaluating galvanic corrosion tests.

"Recommended Methods for Determining Physical Properties of Polymeric Materials Exposed to Gasoline/Methanol Fuel Mixtures." SAE Cooperative Research Program. October 1993.
Detailed tests and procedures for determining worst case fuel blend; conditioning test specimens prior to testing; individual testing for properties of polymers exposed to methanol-gasoline fuel mixtures

Rodriguez, C.F., J.P. Cuellar, Jr. "Evaluation of Fuel Additives to Reduce Engine and Fuel System Material Problems with Methanol-Gasoline Blends." In Proceedings of the Twentieth Automotive Technology Development Contractors' Coordination Meeting, Dearborn, MI. October 25-28, 1982.
Testing of commercial additives in four methanol-gasoline blends (2.5, 5, 10, and 20 percent methanol) to assess inhibition of corrosive effects. Ten metals (magnesium, brass, bronze, copper, terneplate, aluminum, zinc, carbon steel, stainless steel, cast iron) tested for corrosivity, twelve polymers (two nitriles, fluorocarbon, neoprene, epichlorohydrin, fluorosilicon, acetal resin, polypropylene, polyethylene, nylon, perfluorocarbon, cork) tested for compatibility. Three additives were found to inhibit corrosive effects on some metals, and no effects by the additives were noted on polymeric materials that were not attributed to the methanol fuel blend.

Ryan, T.W., D.W. Naegli, E.C. Owens, H.W. Marbach, J.G. Barbee. "The Mechanisms Leading to Increased Cylinder Bore and Ring Wear in Methanol Fueled S.I. Engines." SAE Paper 811200. October 1981.
Investigation of mechanism leading to excessive ring and cylinder bore wear from operation of spark-ignition engine on neat methanol. Suggested that wear results from reactions between combustion products and cast iron cylinder liner.

"Status of Alcohol Fuels Utilization Technology for Highway Transportation: A 1981 Perspective, Volume I – Spark-Ignition Engines." DOE/CE/56051-7. Prepared by Mueller Associates, Inc. for U.S. Department of Energy. May 1982.
Review of data collected to date for spark-ignition engines on alcohol (primarily methanol and ethanol) fuel characteristics, exhaust and evaporative emissions, performance, fuel economy, vehicle drivability, materials compatibility, engine/vehicle design considerations, and environmental, health, and safety implications. Indicates that "engine lubrication and corrosion protection will present challenging problems in the case of some neat-alcohol-fueled vehicles, particularly those operating on neat methanol and/or in low-temperature ambients." Provide test data on wear of aluminum, iron, copper, chromium, tin, and lead by mileage of operation on neat methanol.

"Status of Alcohol Fuels Utilization Technology for Highway Transportation: A 1981 Perspective, Volume II – Compression-Ignition Engines." DOE/CS/56061-8. Prepared by Mueller Associates, Inc. for U.S. Department of Energy. November 1982.
Review of data collected to date for compression-ignition engines on alcohol (primarily methanol and ethanol) fuel characteristics, exhaust and evaporative emissions, performance, fuel economy, vehicle drivability, materials compatibility, engine/vehicle design considerations, and environmental, health, and safety implications. Indicates that long-term engine wear and fuel systems material compatibility is still unproven and extensive testing is required.

"Storage and Handling of Gasoline-Methanol/Cosolvent Blends at Distribution Terminals and Service Stations." API Recommended Practice 1627. American Petroleum Institute. August 1986.
Summary of metals, elastomers, and polymers that are and are not recommended for use with gasoline-methanol/cosolvent blends (mixture of unleaded gasoline, methanol, a cosolvent, and corrosion inhibitors, as approved by the U.S. EPA waiver provisions under the Clean Air Act) in storage and handling at distribution terminals and service stations. Describes special material requirements for individual storage and dispensing components.

5. Recommended Methanol Fuel Blends

In this report, we looked at the possibly of using methanol low level gasoline blends and as a neat fuel in light and heavy duty applications. This section reviews our findings and provides recommendations.

5.1 Low-level blends

There are three possible options for blending methanol with gasoline: splash blending with conventional gasoline, splash blending with gasoline ethanol gasoline, and blending with a formulated RBOB. There are currently only two pathways that will allow methanol blending—EPA's substantially similar interpretation and fuel waivers granted by EPA. EPA's substantially similar interpretation would allow up to 2.75 percent vol of methanol (with equal cosolvent) for gasoline-oxygenate blends. Several waivers have been granted but whether they will still be valid with today's fuels is open to question (especially gasoline ethanol blends).

Splash blend with conventional gasoline

We believe the waivers for methanol would still be valid for blending with conventional gasoline. However, most gasoline will in the very near future contain ethanol and we are not sure whether the waivers will still be valid.

Several other issues will also affect splash blending of methanol. Gasoline volatility is very constrained and adding methanol without adjusting the base gasoline vapor pressure would not be allowed in most regions of the U.S.   Wintertime blends with higher volatility limits may be possible, but other factors such as driveability would also have to be considered. Commingling could also be a problem relative to increased evaporative emissions.

Splash blend as methanol-ethanol blend in conventional gasoline

Splash blending with ethanol gasoline blends will have many of the same issues as splash blending with conventional gasoline: volatility and commingling. Another possible route would be to use methanol as the denaturant for ethanol. However, current ASTM D4804 prohibits the use of methanol as a denaturant.

Blended with RBOB

This is probably the only way methanol could be introduced into the gasoline market and still meet all the current requirements on volatility, emissions performance, and driveability. Further, we believe that the blend would have to be some combination of methanol, ethanol, and reformulated gasoline blend stock (RBOB). Although Brazil in the past used a combination methanol-ethanol blend during times of ethanol shortages, to our knowledge there has been little to no work done to quantify the effect of such blends on the performance of today's vehicles. Automakers and fuel station component manufactures will be concerned with material compatibility issues especially regarding the gasoline legacy fleet and existing fueling infrastructure. Use in high levels blends (e.g. E85) might be acceptable but substantial emissions, vehicle, and material testing would be needed.

Finally, some states like California would also require that any new blends of methanol, ethanol, and gasoline under go multimedia impact analysis.

5.2 High-level blend in light and heavy-duty applications

Current prices do not indicate a large enough consumer benefit for using M85 as a light duty fuel in methanol FFVs. Our analysis shows the lifetime saving over 10 years ranges from a low of $144 to a high of $1,260. We do not believe these savings are significant enough to encourage consumers to purchase a methanol compatible vehicle and to use methanol (assuming the vehicles cost more and methanol, although available, is not as widely available as gasoline). Again, probably the best way to get methanol into this market is to blend—with all the above issues solved—methanol with gasoline ethanol blends and possible restricting use to current and new FFVs and newly designed vehicles.

Our preliminary analysis of the economics of heavy duty applications indicate that methanol could offer a significant value proposition to the end user. Further work is need to compare the economic viability of methanol in various heavy-duty market segments to diesel, but also to other alternative fuels like natural gas and electricity. If viable, then engine manufacturers and suppliers would have to be convinced to develop and produce engines and vehicles that could operate on methanol.

5.3 Final Thoughts

Methanol as a transportation fuel has several advantages:

- Liquid fuel and can be distributed and used like current conventional fuels—gasoline and diesel
- Fuel properties are favorable and engines can be designed to maximize performance. However, today's vehicles, whether diesel or gasoline, are achieving near zero emissions of criteria pollutants so methanol's previous advantage is marginalized.
- Methanol is a viable petroleum displacement strategy, but is not a GHG strategy unless engine efficiencies can be improved over the potential improvements in conventional fuels or significant volumes or renewable methanol can be produced
- Methanol has a number of possible ways to enter the transportation market—as a neat fuel for FFVs and purpose built heavy duty vehicles or as a blend in ethanol-gasoline blends. The later is probably the easiest route, but will require substantial work on fuel formulation, vehicle and fuel emissions, and vehicle driveability. It may be possible that the current FFVs could use a methanol, ethanol, gasoline blend, but again this will have to be verified.

5.4 Research Needed

Itemized below are some ideas of the research we feel is necessary in order for methanol to again be considered as a possible alternative fuel for transportation applications. We have divided our comments relative to low level blend research and high level blend research. These comments are aimed at the use of methanol in the U.S market and would be different for other countries.

Low Level Blends

- Research viability of current methanol waivers or "substantially similar" blend pathways for methanol in U.S. gasolines—Federal RFG, Federal oxygenated gasoline, California RFG, and conventional gasoline. As subset of this effort, determine the blend characteristics of methanol added to these gasolines.

- Assess the possibility of using methanol as a denaturant in ethanol. Determine effects of methanol and methanol-ethanol blends and subsequent RBOB blending. Assess health and safety tradeoffs including human health effects like ingestion, as well as spill effects on soil and water and possible spill remediation.

- Assess material compatibility (vehicles and fueling infrastructure) of viable low level methanol blends compared to gasoline and gasoline ethanol blends.

High Level Blends

- Perform study to quantify the benefits (economic, environmental, petroleum displacement) of using methanol and methanol blends in light and heavy duty applications.

- Research material and engine changes necessary to existing ethanol FFVs to operate on methanol, ethanol, gasoline or any mixtures of these fuels.

- Develop and demonstrate an alcohol (methanol and ethanol) FFV at meets very low emission standards (California PZEV or Federal Tier 2 Bin 2 standards)

- Perform a comparative analysis of methanol, diesel, and natural gas use in heavy duty vehicles. Assess engine efficiencies, emissions, range, and lifecycle costs.

- Develop and demonstrate high efficiency methanol engines for heavy duty applications.