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COMPATIBILITY OF METHANOL FUEL BLENDS WITH GASOLINE VEHICLES AND ENGINES IN INDONESIA

Abigail Martin and Jane O'Malley

www.theicct.org

communications@theicct.org

twitter @theicct

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International Council on Clean Transportation
1500 K Street NW, Suite 650
Washington, DC 20005

communications@theicct.org | www.theicct.org | @TheICCT

EXECUTIVE SUMMARY

Energy independence is of growing interest in Indonesia, and the country is currently a net importer of gasoline. To help close the deficit between gasoline consumption and domestic supply, Indonesia's Ministry of Energy and Mineral Resources (MEMR) and its state-owned oil company, Pertamina, are considering blending 20% by volume alcohol, or A20, into gasoline using domestically produced alcohol. A20 is a mid-level alcohol gasoline blend that consists of 15% methanol and 5% ethanol.

This study surveys the literature to highlight the advantages of and risks associated with utilizing mid-level methanol-gasoline blends on unmodified light-duty vehicles, two- and three-wheelers, and small engines such as those found in lawn and construction equipment. We find evidence that methanol-gasoline blends might improve performance-related properties including octane rating, power and torque, and combustion emissions, depending on the engine configuration. However, those benefits could be outweighed by decreased volumetric energy content, increased phase separation risk, increased material corrosion, and increased fuel volatility, all of which are associated with methanol. These conditions can lead to increased fuel consumption, shorter material lifespans, vehicle stalling, and other drivability concerns.

One of the primary areas of concern with mid-level methanol blends is material compatibility. Alcohols such as methanol are more corrosive than gasoline, and this causes faster degradation of the metals, alloys, and polymers present in vehicle and equipment fuel systems and retail fueling infrastructure. Material degradation can lead to shorter material lifespans, risk of fuel leakage, fire hazard risk, and increased deposits in fuel systems. Some of these problems can lead to decreased drivability of vehicles and increased risk of engine failure.

A few countries have addressed these potential risks by utilizing preventative measures while conducting fleet trials with methanol blends or when integrating methanol into transportation fuel. These countries include, but are not limited to, China, Israel, and Italy. Measures to mitigate compatibility risks include only using methanol-gasoline blends in either methanol-compatible (i.e., flex-fuel) vehicles or newer vehicles; limiting fuel exposure to the atmosphere, contaminants, and water; reducing sulfur and aromatic content in the fuel; upgrading non-alcohol compatible materials in transport, storage, and retail fueling infrastructure; and adding anti-corrosion inhibitors and co-solvents such as ethanol to the fuel. These modifications all come with added costs and require both labor and attention.

While all unmodified vehicles are incompatible with alcohol to a certain extent, Indonesia has specific challenges in introducing A20. These include the high sulfur and aromatic content in Indonesia's base gasoline, the likely large percentage of older, particularly alcohol-incompatible vehicles and small engines in the fleet, and the elevated risks from Indonesia's hot and humid climate, such as increased water contamination through condensation, increased chance for vapor lock through fuel vaporization, and increased corrosion rates. The potential risks and extra capital and maintenance costs associated with adopting A20 are likely to be significant.

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INTRODUCTION

Indonesia is the ninth largest gasoline market in the world and is heavily reliant on fuel imports (U.S. Energy Information Administration, 2021). Between 2013 and 2018, Indonesia imported roughly 320,000 barrels of gasoline per day (Xie & Harjono, 2020a), equivalent to 57% of annual consumption. To reduce reliance on imports and strengthen energy security, Indonesia's Ministry of Energy and Mineral Resources (MEMR) and government-owned oil company, Pertamina, are considering blending alcohols with gasoline (Widyawati, 2020). The proposed gasoline-alcohol blend, A20, would be composed of 80% gasoline, 15% by volume methanol, and 5% by volume ethanol (Meilanova, 2021). This blend would be used in all major gasoline products sold, including Pertamina's Premium[1] (RON 88), Pertalite (RON 90), and Pertamax (RON 92). The A20 blend would also apply to smaller fuel retailers including Shell, AKR, and Vivo.

Motorcycles are the most common vehicle on Indonesian roads. In 2018, Statistics Indonesia reported that the country's motor vehicle fleet was 84% motorcycles and 12% passenger cars (Central Bureau of Statistics, 2019). Although motorcycles consume less energy than passenger vehicles, they still account for a large portion of Indonesia's energy demand. In 2018, motorcycles made up 41% of the total transportation sector energy demand and passenger vehicles made up only 12% (Secretariat General of the National Energy Council, 2019). Motorcycles and three-wheelers with engine displacement greater than 50 cubic centimeters (cm^3) have followed Euro 3 emission standards since 2013 and vehicles with engine displacement less than 50 cm^3 have followed Euro 2 standards since 2005 (Shao et al., 2020). Indonesia's motorcycle industry association (AISI) and the Ministry of Environment and Forestry (MoEF) have discussed adopting the Euro 5 standard for motorcycles in coming years. As of 2018, all new gasoline vehicles sold in Indonesia follow the Euro 4 emissions standard with a goal to implement the Euro 4/IV standard for all vehicles, including those that run on diesel, next year (Xie & Harjono, 2020b). However, the government will take another three years to mandate the fuel sulfur limit corresponding with the Euro 4/IV standard (50 ppm). Both passenger and motorcycle vehicles currently on the road are of different model years and emission standards, and thus the effects of methanol blended fuels on various engine configurations and vehicle components are considered.

Indonesia's current infrastructure and vehicle fleet were not designed to handle alcohol fuels. It is widely known that utilizing mid-level gasoline-alcohol blends in unmodified fueling infrastructure and vehicles could lead to poorer driving performance and material compatibility issues with retail fuel pumps and fuel systems, especially in older vehicles. Methanol could also impair engine performance in machines with small engines such as lawnmowers and leaf blowers (Arendt, 2019). Modifications to vehicles and fueling infrastructure can mitigate these risks, but these modifications involve added costs and attention. This study explores these considerations in the literature and discusses methanol-vehicle compatibility concerns in the Indonesian context. We synthesize results from nearly 30 vehicle performance, material compatibility, and exhaust emissions studies conducted using alcohol-gasoline blends. Studies from any region in the world were considered, but we highlight real-world applications in China, Italy, and Israel.

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[1] Unlike in the United States, Pertamina's "Premium" gas has the lowest octane number of all gasoline sold on the market.

ALCOHOL BLENDING AND FUEL QUALITY

Blending alcohols like methanol and ethanol into gasoline can improve fuel quality. Alcohols are sulfur-free and could help reduce fuel sulfur concentrations when blended into gasoline. Sulfur in gasoline is undesirable because it contributes to air pollution and affects the performance of vehicles' emission control systems such as catalytic converters (Methanol Institute, 2016). Consistent with Indonesia's current Euro 2 standard for passenger vehicles, most of the gasoline sold today is limited to 500 ppm sulfur content. The 500 ppm sulfur limit applies to fuels including Pertamina Premium (RON 88), Pertalite (RON 90), and Pertamax (RON 92). Out of these three fuels, Pertalite is the most popular and accounts for almost 70% of the market (Xie & Harjono, 2020b). The only fuels that adhere to Euro 4/IV sulfur limits of 50 ppm today are Pertamina's Pertamax Turbo and Racing (RON of 95+) and high-octane fuel sold from smaller suppliers. Combined, these fuels make up only 1% of the gasoline market.

Another advantage of methanol is its high-octane number relative to gasoline (Singh et al., 2020). Higher octane reduces knocking, which occurs when there is premature and uneven combustion within the engine. Knocking can damage a vehicle's piston and cylinder walls (CarsDirect, 2013). While fuel octane can also be increased by increasing the aromatics content, this is often discouraged due to aromatics' high toxicity and associated health hazards (U.S. Environmental Protection Agency, 2013). Many countries outside Indonesia limit overall fuel aromatic content to 35% by volume and specifically limit benzene content to between 0.8% and 1% by volume. Meanwhile, most of the gasoline sold in the Indonesian market has a 40% aromatic limit and 5% benzene limit. RON 88 has no limit on benzene or overall aromatics content.

Since methanol acts as an octane booster and contains no aromatic compounds, it can help meet modern emission and fuel quality standards. However, methanol-gasoline blending by volume percentage remains strictly limited in the United States and Europe due to material corrosion concerns. The European Union's Fuel Quality Directive (2009/30/EC) restricts gasoline methanol content to 3% by volume. In the United States, only up to 0.3% methanol can be blended into gasoline by volume or up to 2.75% by volume when it is blended with other co-solvents (IEA-AMF, n.d.).

METHANOL'S IMPACT ON THE PERFORMANCE OF PASSENGER VEHICLES

Mid-level methanol gasoline blends such as A20 can affect the performance of vehicles in several ways, including drivability. Drivability is considered to be improved when there is smoother and steadier driving and acceleration, and decreased drivability occurs when there are frequent hesitations, surges, rough idling, or stalling events (Publow & Grinberg, 1978; Koenig et al., 1976; Agarwal et al., 2021). The effects of methanol blending on both drivability and other fuel performance parameters are discussed below.

POWER AND TORQUE

Greater power and torque are desirable for vehicle operation because they enable faster acceleration at all speeds, higher maximum speed, and the ability to bear larger loads (Anand, 2020). Alcohols, especially methanol, can generally be expected to deliver higher power and torque because of the increased knock resistance, increased heat adsorption, and higher laminar flame speed. Laminar flame speed is the speed at which the oxidation reaction takes place during combustion, and it is correlated with combustion efficiency. However, the addition of alcohol does not guarantee higher power and torque in all engines. If a fuel system is unable to increase the volume of fuel delivered, power and torque can decrease. These effects are especially important for alcohol-based fuels due to their high oxygen content.

Unlike gasoline, alcohols contain oxygen, and this alters the combustion air-to-fuel ratio (AFR). If fuel systems are unable to compensate for highly oxygenated fuels, this may result in an overly lean mixture. Engines achieve the greatest power at roughly 10% fuel enrichment; thus, burning fuel in the presence of excess oxygen will reduce maximum power (Heywood, 2001). Methanol is approximately 50% oxygen and ethanol is roughly one-third oxygen (Robert Bosch GmbH, 1995). To maintain AFR at stoichiometry for each fuel, delivery of methanol must increase 131% relative to gasoline while delivery of ethanol must increase 64%.[2] For A20, this means total fuel delivery must be increased by roughly 16.2%. If engines are equipped with oxygen sensors (i.e., closed-loop operation), they can deliver additional fuel to optimize the AFR and increase performance. Newer vehicles tend to be closed-loop and therefore can adjust the fuel delivered to maintain the AFR automatically.

Alcohols also have a modestly high energy output for a given amount of air flow into the engine due to their high ratio of hydrogen to carbon. For ethanol, the theoretical increase in energy at stoichiometry is 3.2% and for methanol, it is 6.7%. Thus, the theoretical increase in performance for A20 is 3.2% for ethanol times 5% content plus 6.7% for methanol times 15% content, or about 1.2% in total. However, this increase in power and torque only occurs if the fuel injectors or carburetor can deliver more fuel than designed. And even closed-loop systems can run lean during wide-open throttle conditions (Knoll et al., 2009), thus negatively affecting performance and drivability. High temperatures and premature engine damage can also occur as a result of alcohol blending in engines not designed for optimized fuel control. These effects might occur in older vehicles and two- and three-wheelers without oxygen sensors, during open-loop operation, and in small engines.

In order to improve power and torque beyond the higher energy content of alcohols, the engine must both be able to deliver more fuel when alcohols are detected and be modified to take advantage of the higher octane rating and faster laminar flame speed. Small performance improvements can be obtained by advancing the spark timing,

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[2] Fuel delivery rates are calculated based on the AFR stoichiometry for each fuel type. This is equivalent to 14.8:1 for gasoline, 9.0:1 for ethanol, and 6.4:1 for methanol

but significant improvements would require more substantial changes. These include running the engine at richer AFR, designing the engine with a higher compression ratio, or increasing turbocharger boost when the engine computer detects that alcohols have been added to the fuel. Older vehicles and small engines can be manually adjusted to maintain the AFR, but real-time adjustments cannot be achieved.

In laboratory studies, methanol-gasoline blends tend to demonstrate increased power and torque under most speeds and driving conditions if the AFR is maintained. A study comparing Pertalite to M30 (70% Pertalite and 30% methanol) in a four-stroke motorcycle engine found M30 produced higher torque and power than neat Pertalite except at high speeds of RPM above 7,500 (Wayan Sugita et al., 2019). Although engine speed is not directly translatable into driving speed, speeds above 7,500 RPM are likely reflective of highway driving conditions for standard motorcycles.

A different laboratory study found that if an engine with a set ignition timing and AFR undergoes wide open throttle (WOT), power and torque will decrease proportionally as methanol blend level increases (Liu et al., 2007). After adjusting the ignition timing to optimize the AFR, the authors found that power and torque remained constant under WOT. WOT refers to maximum acceleration or “flooring it” but can also occur during engine startup to adjust the air-fuel ratio in vehicles equipped with carburetors.

The same trends are also seen in fleet trials. In Israel, Dor Chemicals and Fiat Chrysler Automobiles tested new Fiats with closed-loop control using M15. Improved or constant power and torque at all tested conditions above 3,000 RPM were demonstrated (Antverg et al., 2017). These measurements were not made in accordance with the European emissions standard. However, in Chinese fleet trials where unmodified and older vehicles ran on M15 (10% methanol, 5% methyl tert-butyl ether [MTBE]), maximum power and maximum torque decreased by 10% and 8%, respectively, compared to gasoline (Xlaofu, 1989). Thus, older vehicles, and two- and three-wheelers unable to adjust the fuel delivery to maintain AFR present performance concerns when running on methanol blends. Although it is unclear how prevalent older engines are on the road in Indonesia today, an estimated 85% of vehicles in the country used outdated technology such as carburetors in 2001 (Steckdaub & Sekartini, 2001).

VOLUMETRIC ENERGY CONTENT

Methanol contains about half the energy of gasoline on a volumetric basis and thus a tank filled with methanol-blended fuel will offer a shorter driving range than the same tank filled with gasoline. The lower volumetric energy content was demonstrated in field and bench tests in China where Jiefang and Dongfeng model trucks drove collectively 34,000–50,000 km on M15 and consumed 2%–4% and 2%–7% more fuel, respectively (Xlaofu, 1989). In a chassis dynamometer test, Eyidogan et al. (2010) also reported that a light-duty vehicle running on methanol blends required more fuel to achieve the same level of wheel power.

One measurement that demonstrates the decreased volumetric energy content of methanol during engine operation is brake specific fuel consumption (BSFC). BSFC is a function of mass flow rate and power and is used to measure the thermal efficiency of internal combustion engines (ICEs). Lower BSFC corresponds with increased engine efficiency.

A study conducted at Jakarta State University tested an engine at high RPM values of 5,000 to 8,500 RPM and found that the BSFC was, on average, 63% higher for M30 (30% methanol and 70% Pertalite) relative to 100% Pertalite (Wayan Sugita et al., 2019). This is higher than the 30% increase in BSFC expected in theory. Studies conducted in China and Turkey also saw a trend in increased BSFC with alcohol fuel blends; one observed a 1% higher BSFC by mass with M15 compared to gasoline (Xlaofu, 1989) and another recorded 3.3% and 1.2% higher BSFC with M10 at 80 and 100 km/h, respectively (Eyidogan et al., 2010). Another trend these studies observed was that the increase in BSFC was larger when the vehicle operated at higher speeds.

Even though alcohol gasoline blends have a lower volumetric energy content and thus higher BSFC, this effect is lessened by the fuel combusting more efficiently. This is why increased BSFC is usually seen in tandem with increased brake thermal efficiency, a function of thermal and mechanical efficiency, when vehicles use alcohol-gasoline blends (Ijaz Malik et al., 2021). Because of the increased fuel consumption that is seen in vehicles using methanol-gasoline blends, increased combustion efficiency does not fully make up for lost volumetric energy content.

EXHAUST EMISSIONS

Methanol's high oxygen content and lack of carbon-to-carbon bonds tends to result in cleaner, more efficient, and soot-free combustion (Ijaz Malik et al., 2021). However, the emissions benefits are highly dependent on the mode of engine operation.

For vehicles with "three-way" catalytic converters, common since the 1980s, it is essential to maintain the AFR at stoichiometry when alcohols and their additional oxygen are added to the fuel. If fuel delivery is not increased to maintain stoichiometry (i.e., open-loop operation), the engine will run lean and there will be no NO_x reduction (Campbell et al., 2000). Unlike NO_x, HC and CO exhaust emissions are expected to be lowest during open-loop operation. This is because the high oxygen content of alcohols generates lean combustion conditions that facilitate CO and HC oxidation. During closed-loop operation when the AFR is maintained, HC and CO reductions are expected to diminish.

A study conducted by researchers in Pakistan found that using M12 instead of gasoline reduced CO and HC emissions, but increased NO_x emissions by more than 30% (Ijaz Malik et al., 2021); this suggests the engine did not have closed-loop controls. Another lab study that used a motorcycle engine with Pertalite as the base gasoline found that M30 generated less CO and less HC emissions than gasoline at most RPMs tested (Wayan Sugita et al., 2019). In Israel's M15 fleet trial, automakers observed decreased CO, HC, and particulate number (PN) emissions with little change in NO_x emissions relative to RON 95 gasoline (Antverg et al., 2017). This observation was also seen in a study in conducted in Shaanxi, China (Liu et al., 2007). Generally, HC and CO emissions decrease, and NO_x emissions vary with methanol gasoline blends.

PHASE SEPARATION

In alcohol-gasoline blends, phase separation occurs when the fuel's water content exceeds a critical limit (Lojkásek et al., 1992). Upon separation, the fuel forms two layers: a gasoline concentrated layer and an alcohol-water concentrated layer. Methanol and ethanol gasoline blends are prone to phase separation because of the alcohols' ability to absorb and mix with water. Alcohols are fully miscible with water due to their high dipole moments (Olah et al., 2009). When a molecule has a high dipole moment, that means that the molecule is polar or has positively and negatively charged regions. For methanol and ethanol, the oxygen in the alcohol's hydroxyl group (-OH) is negatively charged while the carbon and hydrogen in the hydroxyl group are positively charged. The polarity of the methanol and ethanol is an important property because it enables both compounds to form hydrogen bonds with and fully mix with water (Bharath & Arul Mozhi Selvan, 2021). Meanwhile, gasoline primarily consists of hydrocarbon molecules, so it has a low dipole moment or is nonpolar, and therefore does not mix with water (Klein, 2020). This is why excessive water in alcohol-gasoline blends causes separate layers of gasoline and alcohol-water to form.

One reason why phase separation is undesirable is because corrosivity will increase in the bottom of the tank, where the polar alcohol-water layer resides (Agarwal et al., 2021). Another reason is that the upper layer of concentrated gasoline will have a lower octane rating due to less methanol being present. If phase separation occurs before entering a vehicle, such as in an underground storage tank, this could result in out-of-spec fuel that must be disposed of by the retail fueling station; it could also result in highly corroded tanks. These effects could ultimately lead to temporary shut downs at fueling stations (Jain, 2015). If it occurs in a vehicle fuel tank, this may result in increased knocking, vehicle stalling, and engine damage (Franklin Fueling Systems, n.d.; Gas Devices, 2019). Phase separation can result in high service and repair costs for retail fueling stations and vehicle owners, and thus should be taken seriously.

One important factor that affects phase separation risk is temperature. As the temperature decreases, the water tolerance level, or the water holding capacity of the fuel, decreases, and this means a higher likelihood of phase separation (Lantz, 2019; Linder, 2012). Lower temperatures decrease water tolerance levels because as temperatures decrease, more hydrogen bonds form between water and alcohols, due to the molecules' closer proximity. Even though the Indonesian climate is typically very hot and its fuel has higher a water tolerance relative to colder climates, phase separation remains a concern because Indonesia's high humidity increases the possibility of water contamination. Put another way, although Indonesia's weather conditions enable higher water tolerance, weather conditions also increase the likelihood of water entering the fuel, and that increases the chance of phase separation.

Another factor that affects the likelihood of phase separation is the amount of alcohol blended in. The risk of phase separation is higher with low-to-mid methanol blended fuels, such as A20, than with high methanol blends. This is because higher level blends (greater than 30%) have increased water tolerance (Menrad & Nierhauve, 1983).

VOLATILITY

One of the largest concerns with methanol-blended fuel is high volatility. Reid vapor pressure, or RVP, measures a fuel's volatility; the higher the RVP, the more likely a liquid fuel is to vaporize. Excessive fuel vaporization is problematic because vapors can block the vehicle's fuel line and lead to decreased drivability (Agarwal et al., 2021). Neat or pure methanol has low RVP of 32 kPa while blended methanol has RVP ranging up to 85 kPa (IEA-AMF, n.d.; Methanol Institute, 2016). RVP is typically measured at 37.8°C (100°F). The largest increases in RVP occur at low methanol blends; beyond 3% blending, RVP increases begin to level off.

For M15, the RVP of gasoline, 62 kPa, is raised to 84.5 kPa (Methanol Institute, 2016). This is because strong hydrogen bonding stabilizes the liquid in neat methanol (Gaspar et al., 2019). When methanol is blended with hydrocarbons, the hydrogen bonds are broken, and as a result, the mixture becomes azeotropic, altering its boiling point (IEA-AMF, n.d.). Although neat methanol has a lower RVP than gasoline, its blended RVP is greater than both fuels due to this effect.

Vapor pressure ranges are commonly set for fuels to prevent either low or excess levels of vaporization. To give context for common vapor pressure ranges, the Israeli standard (SI 90 Part 4) for M15 limits vapor pressure between 50 and 80 kPa in the winter and 45 and 68 kPa in the summer (Antverg et al., 2017). If the vapor pressure is too low, cold starting and drivability issues may become prevalent. If the vapor pressure is too high, then excessive amounts of fuel will evaporate, block the fuel line (i.e., vapor lock), and once again lead to drivability problems (Agarwal et al., 2021). Because of Indonesia's hot climate, vapor lock is more of a concern.

Vapor lock is also more common with slow or stop-and-go traffic (Grabner Instruments, n.d.). Therefore, vehicles in Indonesia have always faced risk of vapor lock due to the hot climate and heavy traffic in urban areas like Jakarta. Alcohol content generally reduces the temperature at which vapor lock occurs; thus, higher methanol blends have increased risk for this condition. To fully understand this risk of vaporization in an engine fuel system, the vapor/liquid ratio should be tested for A20 fuel. This can be done via the ASTM D5188 testing standard.

MATERIAL COMPATIBILITY CONCERNS WITH METHANOL

A large concern with methanol is its corrosiveness to materials present in engine-fuel systems and fueling infrastructure. Materials of concern include metals, alloys, polymers, and elastomers (i.e., elastic polymers). If proper steps are not taken to account for this risk, engines or fueling infrastructure could experience a shorter lifespan and/or failure.

CORROSION

Alcohols are corrosive due to the increased conductivity from their polar hydroxyl group. Corrosion rates are further increased when the fuel also contains other polar contaminants such as water, absorbed atmospheric oxygen, sulfur, ions, and any other acids or bases (Groysman, 2014; Westbrook, 1999; Bechtold, 1997; Menrad & Nierhauve, 1983).

Even though corrosion risk is highest with water contamination, it can still occur with no water or small amounts of water present. This form of corrosion is called dry, chemical, or alcoholate corrosion (Westbrook, 1999). In this case, electrons from a metal or alloy react with the alcohol and oxygen in ambient air. Corrosion films of oxides and hydroxides then deposit on the metal surface. Corrosion films or products have desirable properties because they provide a protective layer on the metal to prevent deeper metal degradation. However, corrosion products pose risks, as well, especially if they dissolve in the fuel. High quantities of corrosion products can lead to clogged fuel filters (Groysman, 2014). If corrosion deposits pass through fuel filters, they might diminish the power, efficiency, and drivability of the vehicle (Lantz, 2019). Corrosion deposits can be harmful to fuel pumps and fuel level sensors, as well. If deposits settle on the electrical contacts of fuel pumps, the pump may run hotter, resulting in a reduced pump lifespan or pump failure. If the deposits settle on the fuel level sensor, the fuel level gauge may operate incorrectly. In engines equipped with carburetors, corrosion products can clog carburetor jets, which leads to poor drivability that includes hesitations, surging, and rough idling.

While a small number of metals such as titanium and magnesium corrode less rapidly when water is present, most metals and alloys corrode more rapidly with water present (Groysman, 2014). Water generally increases corrosion rates because water is polar and thus conductive. When water is combined with these particles, this forms a conductive or electrolytic solution that can enable new corrosion mechanisms, collectively referred to as electrochemical corrosion. Electrochemical corrosion occurs between two metals immersed in a conductive solution. The conductive solution can strip electrons off one of the metals and thus degrade it. Electrochemical corrosion rates increase as the difference in electrode potential between two metals or alloys increases, and as the presence of ionic contaminants increases (Westbrook, 1999).

Water contamination is of higher risk due to Indonesia’s humid climate, and tanks containing methanol should be properly sealed from the atmosphere because alcohol easily absorbs water vapor (Bechtold, 1997). Water contamination is of particular concern for small, non-road engines that are used intermittently (Hay et al., 2014).

No real-world studies measuring water contamination were found in our review and we therefore look to a laboratory test as an example. In a lab test, 100 ml of methanol sat out in 25 °C with a relative humidity of 55%. Initially, the methanol contained 350 ppm of water and after two hours, water content was 4,200 ppm (Groysman, 2014). This exact scenario is not likely in real world applications, but water contamination could still occur if methanol is inadvertently exposed to the atmosphere via improper sealing during storage or distribution.

High temperatures have been directly linked to increased corrosion. A study from Jyothy Institute of Technology's Centre for Incubation Innovation Research and Consultancy in Bengaluru, India (Meenakshi & More, 2021) found a positive relationship between temperature and corrosion rates of brass. In the study, brass was immersed in various fuels up to a 30% methanol blend rate at an ambient temperature of 30° C or 40° C. The material was then evaluated at 4 days, 10 days, and 30 days. Results showed that the corrosion rate increased as both temperature and methanol content increased, and that the rate of corrosion decreased as time increased. This is assumed to occur because of the protective passive film of corrosion deposits that formed on the metal surface over time. This film can be damaged under turbulent flow conditions that occur in pipelines (Wang, 1997). This could be why the study found higher corrosion rates under flow versus static conditions. Meenakshi and More (2021) only evaluated brass, but a different study from the Jyothy Institute observed the same trends when the same test was performed on two different steel forms (Nandhakrishnan & Thakare, 2020).

Because materials corrode differently under different conditions, it is important that the materials used in Indonesian fueling infrastructure and in the typical vehicle-fuel system be evaluated and upgraded as needed before introducing a new fuel. An overview of common metals used in vehicles and fueling infrastructure and their compatibility is shown in Table 1.

Table 1. Metals commonly used in vehicles and fueling infrastructure and their compatibility with methanol fuel blends.

Metal/ Metal alloy	Corrosion severity	Notes	Sources
Aluminum	Medium-high	• Aluminum hydroxide products can clog filters, corrode fuel injectors, and increase engine wear • Only nickel-plated aluminum should be used	IEA-AMF (n.d.) Menrad & Nierhauve (1983) Groysman (2014) Bechtold (1997)
Bronze	Low	—	Groysman (2014) Bechtold (1997)
Brass	Medium	• Higher water concentration increases corrosion	Bechtold (1997) Westbrook (1999) Meenakshi & More (2021)
Titanium	High	• Stress corrosion cracking and hydrogen embrittlement corrosion occurs with chloride present • One of few metals that corrodes faster with less water present	IEA-AMF (n.d.) Groysman (2014)
Zinc	High	• Higher water, alcohol, and acid concentration increases corrosion risk	IEA-AMF (n.d.) Groysman (2014) Menrad & Nierhauve (1983)
Magnesium	High	• One of few metals that corrodes faster with less water present	IEA-AMF (n.d.) Groysman (2014) Bechtold (1997)
Carbon steel (mild steel)	Low	• Low corrosion risk with no water or impurities present • Corrosion risk sensitive to high water content and impurities (e.g., chloride or sulfate ions, dissolved oxygen, acids) • Compatible material for storage tanks	Groysman (2014) Bechtold (1997) Nandhakrishnan & Thakare (2020)
Galvanized steel	Incompatible	• Not recommended to use with methanol blended fuels • Methanol will strip protective zinc layer and contaminate fuel	Groysman (2014) Dolan (2019) Westbrook (1999) Bechtold (1997)
Stainless steel	Low	• Compatible material for methanol pipelines • More expensive	Nandhakrishnan & Thakare (2020) Bechtold (1997)

Note that while upgrading non-compatible materials is important, it can be difficult and expensive to implement on a large scale. Upgrading costs will vary by country and depending on the existing infrastructure. A study modeling methanol use in China (Nami, 2017) estimated that upgrading storage and distribution infrastructure would cost $80,000 per 10,000 gallons of additional storage capacity and $30,000 to retrofit existing gasoline storage units of the same size.

POLYMER DEGRADATION

Methanol is considered corrosive or aggressive with polymers and elastomers (i.e., elastic polymers), which are used for parts such as seals. When exposed to methanol, polymers might swell and properties such as tensile strength, weight, hardness, and elasticity could change (Westbrook, 1999). This can lead to risk of polymer failure and fuel leakage. If leakage occurs at crucial connecting and sealing parts such as pipe domes, fuel filter housings, seals, gaskets, or fuel lines, a fire risk is created (Menrad & Nierhauve, 1983). Therefore, materials for these parts need to be scrutinized before they encounter methanol gasoline blends. Materials used for pipe domes and gaskets are commonly incompatible with alcohol blends and would likely need to be upgraded to Teflon-based materials (Bechtold, 1997). Usually, elastomers such as Teflon that have a high fluorine content perform best with methanol fuels. An overview of elastomer and polymer compatibility is shown in Table 2. Material use information in Table 2 was gathered from Kass et al. (2020).

Table 2. Elastomers and polymers and their compatibility with methanol blended gasoline fuels.

Elastomer/polymer	Use/applications	Compatible?	Source
FKM **FPM** **Fluorocarbon rubber** **Fluorel** **Viton®**	• O-rings • Seals • Fuel lines • Gas filters • Fuel injectors • Carburetor valves • Carburetor tubing	Yes, with methanol blends (not with neat methanol)	Westbrook (1999)[a] IEA-AMF (n.d.) Bechtold (1997) Methanol Institute (2016) Antverg et al. (2017)
Acetal **Polyoxymethylene (POM)**	• Molded parts • Fuel line valves • Pump and tank components	Yes	Dolan (2019) Westbrook (1999)
Cross-linked polyethylene (PEX)	• Fuel lines	Yes (only polyethylene [PE] is incompatible)	Dolan (2019) Bechtold (1997)
Teflon **Polytetrafluoroethylene (PTFE)**	• Liners • Seal material • Pipe dome	Yes	Dolan (2019)
Fluorosilicone (FVMQ)	• O-rings • Gaskets • Seals	Inconclusive*	Dolan (2019) IEA-AMF (n.d.) Westbrook (1999) Virant et al. (1991) Antverg et al. (2017)
Neoprene **Polychloroprene (CR)**	• Gaskets • Fuel lines • Hose covers • Seals	Not with seals; inconclusive for others	Dolan (2019) IEA-AMF (n.d.)
Fiberglass-reinforced[b]	• Tanks • Pipelines	Only if designed for methanol compatibility	Dolan (2019) Bechtold (1997) Westbrook (1999)
Nitrile butadiene rubber, Buna-N (NBR)	• Fuel lines • Gaskets • Airtight joints	Inconclusive*	Dolan (2019) Westbrook (1999) Bechtold (1997) Antverg et al. (2017)
Chlorobutyl rubber (CIIR)	• Fuel lines • Gaskets	Yes, but not in seals	Westbrook (1999)

Elastomer/polymer	Use/applications	Compatible?	Source
Hydrogenated nitrile butadiene rubber (HNBR)	• Fuel lines • Seals • O-rings	No	IEA-AMF (n.d.)
Polyurethane (PUR)	• Vehicle fuel lines	No	Dolan (2019) Westbrook (1999) IEA-AMF (n.d.) SGS INSPIRE (2020) Bechtold (1997) Antverg et al. (2017)
Polyvinyl chloride (PVC)	• Chemical tanks • Internal linings • Coatings • Sealants	No	IEA-AMF (n.d.) Riedl (2019) SGS INSPIRE (2020)

* Inconclusive means that two or more sources conflicted with each other.

a Westbrook's recommendations assumed the gasoline-methanol blend included a co-solvent.

b According to Westbrook (1999), some fiberglass USTs and piping are only recommended for handling up to limits of E10, M5, or MTBE15.

Fuel quality can also contribute to the swelling of elastomers. High aromatic content in the base gasoline can increase elastomer degradation (Menrad & Nierhauve, 1983). Lowering the aromatic content in the base gasoline is important to reduce elastomer degradation from methanol-gasoline blends.

FLEET TRIAL CASE STUDIES

Several countries and automotive companies have experimented with or implemented low-to-mid methanol gasoline blends in passenger vehicles. A historical overview of fleet trials is presented in Table 3. The country that most prominently blends methanol in its vehicle fleet is China. Other countries not mentioned in Table 3 that have also considered methanol as a transportation fuel include Australia, Egypt, New Zealand, and India (Dolan, 2019).

Table 3. Overview of mid-level methanol gasoline blend fleet trials and findings.

Country/ organization, year(s)	Fuel blend limit	Fleet trial details	Findings	Source(s)
Methanol Institute compilation, 40+ years	• M7 for vehicles with carburetors • M15 for newer vehicles	• 1970s/1980s fleet trial compilation from: • Germany • Sweden • New Zealand • China • California, United States • China M15 Trial (2004)	• Older vehicles with carburetor fuel systems can manage alcohol fuel blends up to 3.7% wt. oxygen (E10 or M7). • Modern vehicles can manage alcohol fuel blends up to 7.5% wt. oxygen (E20 or M15). • For >M3 blend rate, use corrosion inhibitors and co-solvents in vehicles equipped with protected fuel system metals.	Dolan (2019) Methanol Institute (2014)
Italy/FCA, 2017	• A20 (M15/E5) for model year 2001+	• 5 Fiat 500s were rented out 9,000 times and traveled 50,000 km over 13 months • Fuel limited to 10 ppm sulfur, 0.2% water	• A20 compatible with E10 compatible vehicles (i.e., those manufactured in 2001 or after). • Metal tube, O-ring, and plastic tube did not show compatibility issues. • No phase separation issues.	Dolan (2019) ("Eni and FCA," 2019)
Israel/Dor Chemicals/ FCA, 2012	• M15 for newer or methanol-designated vehicles	• Long-distance trial conducted on two Fiat 500 MTA FIRE 1.2 8V Euro 6 vehicles • Fiat car was specifically designed to run on either M15 or gasoline • 220,000 km driven • Fuel mixture: 83% hydrocarbons, 2% co-solvent, 15% methanol	• Three malfunctions where the engine stalled and turned off. Once car was restarted, the car was fine. Issue associated with contamination in fuel. • Slightly improved power and torque on M15. • Increased initial residue accumulation. Issue resolved when oil was replaced every 10,000 km instead of 15,000 km. • Deconstruction of one vehicle after some mileage showed residue in intake manifold, fuel injectors, and intake valves.	Winther, (2019) (“FCA presents Fiat 500 M15” (2016) The Standards Institution of Israel (2016) Antverg et al. (2017)
China, 1983–1985	• M15 (10% methanol, 5% MTBE co-solvent)	• 500 gasoline-based Jiefang and Donfeng Brand trucks traveled for >60,000 ton-km using M15 • BJ-212 Beijing Brand Jeep bench tested on M15 • High-grade methanol was used with the water content limited to <0.025% • M15 saturation vapor pressure: 61.3 kPa	• Normal in terms of wear and lubrication. • Vapor lock problems occurred when temperature was > 32 °C, unless electronic fuel pump was used. • Fuel consumption on M15 in field and bench tests was 1.8%–3.8% and 1.8%–6.7% higher with the Jiefang and Dongfeng trucks, respectively.	Xlaofu (1989)
Italy, 1983	• 7.5% methanol, 7.5% tertiary butyl alcohol (TBA) blend	• Only tested for hot drivability performance • Six carburetor utilizing cars with model year 1982 tested in 30–35 °C	• M15 posed drivability issues in hot weather due to the fuel’s volatility. • 50/50 methanol-TBA blend performed better in hot weather than M15.	Palmer and Tontodonati (1983)

Country/ organization, year(s)	Fuel blend limit	Fleet trial details	Findings	Source(s)
Germany, 1979–1982	• M3 for non-adjusted vehicles • M15 for slightly modified vehicles	• German Alcohol Fuel Test Program sponsored by the Federal Ministry for Research and Technology • 1,000 slightly modified M15 cars collectively drove 33 million miles and consumed 1.7 million gallons of fuel • Carburetor and fuel injection system vehicles considered • Modifications made: material upgrades, adjustment for leaning effect, warm up adjustment, increase fuel circulation to prevent vapor lock, high-energy ignition system • Commercial engine lubricants used	• Slight modifications needed before M15 used. • Co-solvent such as TBA is optimal in 1:1 ratio with methanol. • Higher blend than 3% methanol creates vapor lock, material compatibility, and leaning effect issues. • M15 blends used in unmodified vehicles causes material problems in an elevated number of vehicles, but not all. Material problems pose leakage and thus fire hazards. • Aromatic content in gasoline should be minimized. • Results with M15 on modified vehicles: • Unstable idles and engine stops occurred without fuel detergent. • Some NBR parts failed after 6–12 months. • Few vapor lock issues reported in hot weather and eliminated with modifications. • Normal wear on engine and fuel system.	Menrad and Nierhauve (1983)

Evaluating all the trials shown in Table 3, we see there is no established methanol blending limit recognized by all countries and organizations. However, Table 3 does reveal two things about multiple mid-level methanol gasoline blend trials: (1) older vehicles are far less tolerant of higher methanol blends; and (2) in almost all cases, vehicles require modification before successfully utilizing mid-level methanol gasoline blends. (Modification is also likely to be necessary for non-road engines that are unable to regulate fuel delivery.) Across the set of fleet trials, researchers found that newer vehicles can tolerate methanol blends up to M15 while older vehicles can only tolerate between M3 and M7.

Israel is interested in an M15 gasoline with a 2% co-solvent, and this is of particular relevance to Indonesia. Israel recently completed a successful trial on two Fiat vehicles running on M15; the trial was conducted by Dor Chemicals and FCA (The Standards Institution of Israel, 2016). The M15 fuel was only to be used by vehicles designed for M15, such as the two Fiats from the fleet trial, or vehicles deemed compatible by manufacturers. Throughout the trial, researchers identified some initial issues with M15.

The largest issue was three instances of stalling and shutting down (Antverg et al., 2017), and one time this was due to phase separation and resulted in replacement of the vehicle's fuel pump. Researchers also found that the fuel station's flexible hose was a source of contamination and needed to be replaced. After the trial, the wear on the engine-fuel system was normal or slightly worse, but still acceptable. However, there was notable residue accumulation on the intake manifold and intake valves, and it resulted in a recommendation to change the engine oil every 10,000 km instead of every 15,000 km. As a result of the field trial, Israel's Ministry of National Infrastructures and Energy Water Resources created a new M15 standard, referred to as SI 90 Part 4. Some notable limits within this standard include: 10 ppm sulfur content, 0.1% water content, summer RVP of 45 to 60 kPa, winter RVP of 50 to 80 kPa, and 35% aromatic content.

MODIFICATIONS NEEDED FOR A SMOOTH TRANSITION TO MID-LEVEL METHANOL GASOLINE BLENDS

Success in blending alcohol with gasoline is possible, as evidenced by the experiences of countries other than Indonesia. But this success is not possible without substantial preparation. Such preparation includes upgrading fuels to certain standards, upgrading non-compatible materials in fueling infrastructure and engine-fuel systems, using necessary additives, and modifying older vehicles' operating conditions. The alternative is to only use methanol-gasoline blends with compatible vehicles, two- and three-wheelers, and non-road engines. To keep methanol out of vehicles and engines not designed for mid-level blends, Indonesia would also need to move toward dedicated methanol blend pumps that would only be used for compatible engines.

Because there are multiple contaminants of concern, stringent fuel quality standards need to be set by the Indonesian government if A20 fuel is utilized. A good reference is Israel's SI 90 Part 4 M15 standard (Antverg et al., 2017; Winther, 2019). In this standard, sulfur is limited to 10 ppm, manganese is limited to 2 ppm, water is limited to 0.1%, aromatic content is limited to 35%, and oxygen is limited to 9% by weight. Limiting contaminants in fuels is essential because they typically increase the conductivity of the fuel and thus corrosion rates. Contamination includes excess water entering through loose fittings in pipelines. Excess water can lead to phase separation, so water content in gasoline should be monitored before and after methanol blending occurs.

For vehicles to be compatible with methanol, they must use compatible materials such as NBR, neoprene, and polyurethane for seals, fuel filter housings, and fuel lines. Auto manufacturers could switch to using these materials for new vehicle production. Existing vehicles would need to be retrofitted with these materials in order to be compatible, and that would mean added costs for the consumer.

In retail fueling infrastructure, retailers can upgrade nozzles, retail dispensing hoses, and fuel pump dispenser filters to versions that are methanol compatible. To reduce corrosion deposits from the hose entering vehicles' fuel tanks, fuel filters should have smaller micron openings of 3 μm instead of the typical 10 μm mean diameter (Bechtold, 1997; Methanol Institute, 2016). Filters on dispensers and for vehicle engine oil are commonly secured with glue that is not methanol compatible and should be switched to methanol-compatible glue (Bechtold, 1997). Replacing nozzles, dispensing hoses, and filters with those that contain methanol-compatible materials is crucial for limiting the contaminants that are pumped into consumers' vehicles (Bechtold, 1997). Doing this will protect vehicles from sediments and contaminants that could decrease both drivability and the operational capabilities of fuel system components like sensors and fuel pumps. In places where neat methanol is stored or transported, fluoroelastomers and polyurethane elastomers can also be upgraded to other materials to prevent leaks (Methanol Institute, 2016).

Upgrading non-compatible materials is a difficult and expensive step, but it is also crucial because of the leakage and compatibility risks. Leakage risks are serious because they pose fire and environmental contamination concerns.

Small amounts of additives such as corrosion inhibitors, lubricity additives, and fuel detergents can be used in methanol blends to decrease material wear and corrosion deposits. Corrosion inhibitors are commonly added to methanol-gasoline blends and common corrosion inhibitors include amines, amides, acetates, and sulphonates (Groysman, 2014). Increased wear on vehicles could also occur with methanol fuel blends. This is due to methanol's higher viscosity relative to gasoline (Bechtold, 1997). Engine lubricants can be used to reduce wear (Groysman, 2014; Menrad & Nierhauve, 1983) and another solution is to replace vehicle the engine oil more frequently. This was deemed necessary as a result of Israel's fleet trial, which switched to replacing engine oil every 10,000 km instead of 15,000 km (Antverg et al., 2017). Fuel detergents may also be necessary to protect older vehicles with carburetors. One study found that adding fuel detergent to an older model vehicle running on M15 resolved corrosion issues including deposit formation on carburetors and intake manifolds (Menrad & Nierhauve, 1983).

Co-solvents might also be necessary to stabilize the fuel and increase solubility between the blending alcohol and the gasoline. By increasing the solubility, co-solvents can raise the water tolerance of the fuel before phase separation and reduce any increases in RVP. Co-solvents are more crucial in mid-level alcohol blends like M15 than in high-level alcohol blends like M85, due to reduced stability (Winther, 2019). For an alcohol to be a co-solvent, it must have a higher carbon content per molecule than the blending alcohol, and the higher the carbon content, the better the co-solvent is (Methanol Institute, 2016; Koenig et al., 1976). Commonly used co-solvents for methanol include ethanol, propanol, butanol, isopropyl alcohol (IPA), isobutanol, methyl tert-butyl ether (MTBE), and tertiary butyl alcohol (TBA). Using 5% ethanol as a co-solvent for M15 is being considered and tested by Italy (IRENA & Methanol Institute, 2021).

Because of all the modifications involved, sufficiently preparing to integrate A20 into Indonesia's gasoline vehicle fleet is likely to involve high costs. In addition, there are likely to be increased maintenance costs associated with A20 fuel adoption, especially if the preparation is not thorough. Changing the gasoline to a gasoline-methanol blend will likely dislodge built up sediment from the distribution system and could initially lead to a shortened lifespan of fuel filters in gasoline dispenser pumps (Methanol Institute, 2016). Additionally, more regular checks for free water in fuel storage tanks should be performed. If too much water is present in the fuel blend, the fuel may need to be disposed of and the retail fuel station may need to be shut down temporarily (Jain, 2015). Lastly, Indonesia should monitor pipelines and storage tanks more regularly to confirm that they are fully sealed and are not degrading faster than when they contained pure gasoline. Any loose fittings in pipelines and storage tanks may increase the contaminants in the fuel and thus increase the risk of phase separation and corrosion.

CONCLUSION

We reviewed literature evaluating the technical benefits and risks of mid-level methanol gasoline blends on vehicles and fueling infrastructure. Potential advantages of A20 over pure gasoline include increased power and torque during closed-loop operation and resistance against knocking. Potential problems include increased risk of phase separation, vapor lock, and corrosion and deterioration of metals, alloys, and polymers in vehicles and fueling infrastructure. If realized, such risks might result in decreased vehicle drivability, vehicle stalling, or damage to the engine-fuel system and fueling infrastructure, and thus they should be taken seriously.

Despite the risks, countries including China, Italy, and Israel have successfully completed fleet trials of methanol blending or successfully integrated methanol-gasoline blends. In all cases, the road to success required preventative measures including tightening fuel standards to restrict water, aromatic, and sulfur content, and limiting RVP to a safe range. Other measures included additives such as co-solvents, corrosion inhibitors, and more frequent oil changes. Lastly, mid-level methanol gasoline blends were only recommended to be used by vehicles with oxygen-control sensors or those specifically made to run on methanol blends.

The costs of successfully moving to A20 are not trivial. The high sulfur and aromatic content in Indonesia’s gasoline and its hot and humid climate can exacerbate vapor lock, corrosion, and phase separation risk, in addition to added costs and maintenance. Transitioning most of the gasoline supply to A20 would likely result in high costs associated with updating fuel transport, storage, and pumping infrastructure to alcohol-compatible materials, and confirming that loose fittings are tightened to minimize water and other contaminants entering such as atmospheric oxygen. On top of high upfront capital costs, there are likely to be more maintenance costs for retail fueling pump owners and vehicle owners. Performance issues would also be likely to occur for the majority of non-road engines using open-loop systems.

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