

Review: Fuel Volatility Standards and Spark-Ignition Vehicle Driveability

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ABSTRACT

Spark-ignition engine fuel standards have been put in place to ensure acceptable hot and cold weather driveability (HWD and CWD). Vehicle manufacturers and fuel suppliers have developed systems that meet our driveability requirements so effectively that drivers overwhelmingly find that their vehicles reliably start up and operate smoothly and consistently throughout the year. For HWD, fuels that are too volatile perform more poorly than those that are less volatile. Vapor lock is the apparent cause of poor HWD, but there is conflicting evidence in the literature as to where in the fuel system it occurs. Most studies have found a correlation between degraded driveability and higher dry vapor pressure equivalent or lower $T_{VL} = 20$, and less consistently with a minimum T50. For CWD, fuels with inadequate volatility can cause difficulty in starting and rough operation during engine warmup. The Driveability Index (DI)-a function of T10, T50, and T90-is well correlated with CWD in hydrocarbon fuels. For ethanol-containing fuels, a correction factor to the DI equation improves the correlation with CWD, although the best value for that factor has still not been determined. Ethanol increases the heat of vaporization. However, this is likely insignificant for E15 and lower concentration fuels. The impact of ethanol on driveability is likely due to its direct effect on vapor pressure at cold temperatures. For E51-E83 or flex-fuel blends, ASTM sets a minimum vapor pressure; however, published data suggest that a correction for the amount of ethanol in the fuel is needed to accurately predict CWD, possibly because ethanol has a higher lower-flammability limit.

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INTRODUCTION

Driveability is the smooth delivery of power from an engine to a vehicle in response to driver demands. Poor driveability is associated with difficult starting, rough idle, misfires, surging, hesitations, and insufficient power, all of which can be affected by fuel characteristics. In other contexts, driveability has also encompassed appropriate gearing, handling, steering traits, and ride quality. However, here we are concerned with light-duty gasoline vehicles and those aspects of driveability impacted by fuel characteristics and thus only those aspects of driveability associated with the fuel delivery and combustion systems.

"One of the major problems of the automotive industry has always been to design engines which would give the desired performance with current fuels. The engine should start readily even in cold weather and should keep on running without too many interruptions....The fuel feed system should be constructed so that the fuel is fed in the desired amounts to the intake manifold without serious interruption of flow due to vapor lock.... The petroleum technologist... should know how the fuel behaves in the engine in order that he may intelligently produce the most satisfactory fuel.... He should know, still further, the characteristics of fuels which

determine their performance in the engine and he should have adequate routine tests for the evaluation of these characteristics." -
O.C. Bridgeman, 1934 [1]

This quote, from more than 80 years ago, represents the interplay between vehicle technology and fuel quality needed to ensure good driveability. It was taken from a report of what is perhaps the first cooperative research effort between the automotive and petroleum industries. This cooperative effort, which continues to this day, has yielded vehicles and fuels that effectively meet driver requirements for vehicle operation under virtually all weather conditions. Higher expectations for vehicle performance, vehicle changes in response to stricter pollution control and fuel efficiency requirements, as well as changes in fuel, primarily the use of ethanol and other oxygenates, are driving ongoing research on this subject.

BACKGROUND

Fuel Systems

Fuel systems in recent-model cars are tasked with providing the proper amount of fuel to the engine in order to accomplish the following objectives:



1. Meet ever stricter emission standards and avoid damage to emission control equipment
2. Optimize fuel efficiency under all operating conditions
3. Provide extra bursts of fuel when accelerating, or a more prolonged increase in fuel when the vehicle is going up a hill or towing a heavy load
4. Provide extra fuel as necessary when the engine is cold so it will start
5. Adapt to the different energy contents of fuels, which can range $\pm 4\%$ from average in hydrocarbon gasolines [2], plus an additional reduction of up to 5% when blended with up to 15% ethanol
6. Adapt to changes to combustion stoichiometry caused by the blending of oxygenates.

In this section, we briefly review the fuel supply system in recent-model spark-ignition vehicles to consider how pressure and temperature inside of the fuel system, combined with the volatility of the fuel, may affect the smooth delivery and combustion of fuel.

Historically, spark ignition engines were built with a carburetor to feed and meter the fuel. In a carburetor, the combustion air flows through a venturi. At the throat of the venturi, the reduced pressure entrains fuel into the air flow from the adjacent fuel-filled float chamber. Fuel enters the venturi and is atomized and carried towards the intake manifold. The system is designed such that fuel evaporation begins within the carburetor, continues in the manifold, and then finishes within the combustion cylinder. Carbureted fuel systems were phased out of U.S. cars beginning in the late 1970s and, by the mid-1990s, all new cars had fuel injection systems.

Fuel injectors are valves that precisely time and meter the fuel injection event. The fuel enters the injector as a liquid, is atomized, and mixes with the air supply. The first fuel injectors were single-point or central fuel injection systems located in the throttle (throttle body injectors) that sent atomized fuel into the air supply. From there, the combined air and fuel entered a manifold that fed all the engine cylinders. The manifold was heated by the engine to minimize the potential that cold fuel would condense or collect outside of the combustion chambers. Newer vehicles have multi-port fuel injection (PFI) that times and meters the fuel into each cylinder independently at the intake port from a single pressurized manifold. Carried one step further, direct injection allows the fuel to be injected directly into the combustion chamber, and thus completely eliminates the distance between the point where the fuel is atomized and the combustion zone.

The fuel pump in most fuel-injected cars is submerged inside the fuel tank. In a PFI system, the fuel pump is capable of pressures of up to about 8 bar (120 psi), and the fuel rail line is maintained at 300 to 600 kPa (30 to 90 psi) [3]. Much higher pressures, on the order of 3,500 to 20,000 kPa (500 to 3,000 psi) [4] are required for direct injectors, although these systems are typically built with a lower pressure in-tank lift pump capable of 400 to 600 kPa (60 to 90 psi) [4] to feed the higher pressure system. A constant pressure in the fuel line is maintained using a pressure regulator that releases excess fuel pressure (and fuel) back to the tank. In some cases, the return fuel line is located on the fuel rail

near the injection location. However, in the past decade most cars have the return line within the fuel tank, close to the exit of the fuel pump. The latter is known as a returnless system.

During engine operation, the driver presses the throttle (or accelerator pedal), which directly controls the air supply, while the engine control unit (ECU) responds to real-time information from sensors that measure air flow rate and pressure, throttle position, engine temperature, accessory electrical load, and oxygen in the exhaust to control the rate and timing of fuel delivery. If the ECU determines that extra fuel is needed for startup, catalyst protection, or to prevent overheating of engine parts, the ECU may move into what is known as open loop operation. In this case, the ECU overrides the information from the oxygen sensor and increases the fuel supply, typically increasing carbon monoxide and hydrocarbon emissions and lowering fuel economy.

Driveability Testing Methods

Driveability is typically measured by a trained rater performing a set of vehicle maneuvers on a test track. The rater quantifies the number and severity of malfunctions, including difficulty starting, backfires, stumbles, hesitations, engine stalls, rough idle, misfires, or insufficient power. These malfunctions are quantified and rated as to severity. No absolute standard level of driveability has been developed, and levels of driveability are only considered as relative values. Because of the assumption that most driveability issues are related to fuel that is either too volatile or not volatile enough relative to ambient temperature conditions, testing has generally been divided into tests of hot weather driveability (HWD) for the former problem and cold weather driveability (CWD) for the latter issue.

This review focuses on driveability testing as a measure of vehicle operating problems associated with the behavior of fuel in the fuel system and engine, especially at high and low ambient temperatures. There are a number of other possible sources of poor engine operation at temperature extremes that are unrelated to fuel. For example, at very cold temperatures, the higher viscosity of oil reduces the efficiency of the engine, which might potentially be felt as sluggish acceleration.

Specific problems typically given demerits by trained raters are defined below.

- *Backfire* - an explosion in the induction or exhaust system
- *Engine idle roughness* - based upon the sound and feel from the engine during idle
- *Engine stalls* - engine quits running with the ignition key in the "on" position
- *Extension* - an abnormally slow or sluggish acceleration
- *Hard starting* - excessive cranking time during startup
- *Hesitation* - lack of response to opening the throttle
- *Stumble* - sudden loss of power followed by a resumption of power
- *Surge* - cyclic pulses of power.



The number of demerits assigned to different vehicle operating problems varies. Two typical demerit systems, one employed by the Coordinating Research Council (CRC) since 2001[5] and another recently used by Concaawe [6] are compared in Table 1. The CRC system has evolved since 2001, but it still has the same general outline, and, for the most part, identifies similar faults.

Table 1. Two driveability demerit systems (CRC Report No. 629 [5]/Concaawe 2004-01-02 [6]).

CRC/ CONCAWE	Trace/ Slight	Medium/ Moderate	Heavy ^a	Extreme/ Severe
Backfire	4/4	8/8	12/NA	32/12
Stumble	4/4	8/12	12/NA	32/24
Hesitation	4/4	8/12	12/NA	32/24
Surge	4/3	8/6	12/NA	32/24
Stall	10 × Count in Park/18 when starting; 21 when idling/18, 16 × Count in Drive/42			
Rough Idle	1	2	4	8
Hard Start	1	2	4	8
No Start	32 × no. of tries (3 maximum)/42 after 10 attempts or 1 minute + 10 × (starting time in seconds – 1)			
Acceleration Fail (used only by Concaawe)	42 – Impossible to reach cruising speed defined as 0.9 × max speed after 2 × (acceleration time from 50 km/h to cruising speed on reference fuel) in first test sequence or 4,500 rev/min in third gear in a different test sequence			
Cruise Fail (Concaawe)	42 – cannot maintain cruising speed for longer than 4 minutes			

^aNo comparable Concaawe fault.

Because the number of demerits varies widely between individual vehicles and vehicle makes and models, the CRC log transforms all results. CRC has found that the transform results in a dataset that is more normally distributed. Because most testing is done outdoors, ambient conditions can be somewhat variable. The CRC sets an allowable temperature range for test runs and then typically corrects for any statistical effect within that temperature range. Similarly, corrections to demerit ratings are made for statistically significant differences between raters.

All vehicles in a test program are driven over the same set of prescribed maneuvers. The maneuvers defined by the CRC in various reports are described as follows. “Wide-open-throttle acceleration” means that the vehicle is accelerated as fast as possible without producing tire squeal or appreciable slippage. “Light-throttle acceleration” is defined as immediate “snap” acceleration to reach the intake manifold vacuum reading necessary to attain 25 mph in 9 seconds. The appropriate value of the vacuum for this acceleration must be determined before driveability testing begins. In light-throttle acceleration, the throttle position does not change during the acceleration, as opposed to a “crowd acceleration,” which starts at the same initial throttle position as a light-throttle acceleration, but maintains constant vacuum by increasing the throttle with increasing engine speed. A “detent acceleration” is begun by opening the throttle to just above the downshift position as indicated by transmission shift characteristics, and then maintaining a constant throttle position throughout the acceleration. As with light-throttle acceleration, this value must be determined prior to driveability testing. Detailed test procedures for recent CRC HWD and CWD studies are shown in Appendix 1.

Fuel Properties that Influence Driveability

The key gasoline characteristic affecting driveability is volatility [7]. Gasoline must be volatile enough to evaporate readily in the cylinder when the engine is cold, and yet not so volatile that excessive levels of gasoline vapor accumulate in the fuel system and reduce or interrupt the fuel supply to the engine. Both excessive and inadequate volatility can compromise the operability of the vehicle and result in rough idling, hesitations, stumbles, surges, or backfiring.

ASTM D4814, Standard for Automotive Spark-Ignition Engine Fuel, which was developed cooperatively by the automotive, petroleum, and ethanol industries and other stakeholders, limits both excessive and inadequate volatility to ensure acceptable driveability in most situations. Higher ambient temperatures make it easier for fuels to evaporate and so different levels of volatility in fuel are required for different climates and seasons. Gasoline for cold weather is formulated to evaporate readily while warmer weather blends are required to be less volatile.

Standards that Restrict Excessive Volatility

To ensure that fuels are not too volatile, ASTM D4814 restricts the T50 (minimum) of the distillation curve, the dry vapor pressure equivalent (DVPE) at 38°C, and the temperature at which the vapor to liquid volume ratio is 20 ($T_{V/L=20}$). Requirements for each of these properties vary by season and location to minimize driveability issues at reasonable worst case (high temperature) ambient conditions (Table 2).

Table 2. Standards that restrict excessive volatility in fuel for spark-ignition engines in ASTM D4814-14. Note various combinations of vapor pressure/distillation class and vapor lock protection class are allowed. Exceptions noted in footnotes below.

Vapor Pressure/ Distillation Class	Vapor Pressure, max, kPa (psi) ^a	T50 Min °C (°F) ^b	Vapor Lock Protection Class	Temperature for a Vapor-Liquid Ratio of 20, min, °C (°F)
AA	54 (7.8)	77 (170.)	1	54 (129)
A	62 (9.0)	77 (170.)		
B	69 (10.0)	77 (170.)	2	50 (122)
C	79 (11.5)	77 (170.)	3	47 (116)
D	93 (13.5)	77 (170.)	4	42 (107)
E	103 (15.0)	77 (170.)	5	39 (102)
			6	35 (95)

^aEPA permits some blends containing 9 to 10 vol% ethanol to have a vapor pressure 6.9 kPa (1 psi) higher than that of gasoline.

^bThere are two exceptions that allow a lower T50 minimum of 66°C (150°F):

1. Gasoline/ethanol blends with ethanol concentrations from 1% to 10%, and 2. Volatility Class D and E gasolines that contain no ethanol and will not be used as blendstocks with ethanol.

ASTM D4814 has guidance for determining the appropriate vapor pressure/distillation class in areas outside of the United States that are based on the six coldest or hottest consecutive hourly temperature readings in a day, as shown in Table 3. The 10th percentile minimum represents the likelihood that the 6-hour minimum temperature will be below this value during a month. The 90th percentile maximum represents the likelihood that the 6-hour maximum temperature will be exceeded in the month. The minimum zone temperature ranges for

each vapor pressure/distillation class are somewhat different at higher altitudes to compensate for changes in fuel volatility due to changes in barometric pressure. Within the United States, the vapor pressure/distillation class is specified in a table in ASTM D4814 and generally follows this temperature guidance although there are lower vapor pressure requirements for certain areas in the summer based on U.S. Environmental Protection Agency (EPA) and state regulations to limit fuel evaporative emissions. These requirements are also outlined in detail in ASTM D4814.

Table 3. ASTM D4814-14 guidance for determining Vapor Pressure/Distillation Class and Vapor Lock Protection Class in areas outside of the United States.

10th Percentile 6-h Minimum Temperature, °C (°F)	90th Percentile 6-h Maximum Temperature, °C (°F)	Vapor Pressure/Distillation Class	Vapor Lock Protection Class
>16 (60)	>= 43 (110)	A	1
>10 (50)	<43 (110)	B	2
>4 (40)	<36 (97)	C	3
>-7 (20)	<29 (85)	D	4
</-7 (20)	<21 (69)	E	5
Not specified	Not specified		6

The temperature of the fuel system and the vapor over liquid volume ratio (V/L) that can be tolerated without vapor lock or hot fuel handling problems may vary from vehicle to vehicle. According to ASTM D4814, the temperature at which the vapor/liquid ratio is approximately 20 in ASTM method D5188 shows a good correlation for predicting vapor lock for both gasoline and gasoline/ethanol blends, and has been included in the ASTM specification since 1970, even though the values are based on testing done almost 50 years ago [8]. The $T_{V/L=20}$ is set between 35°C and 54°C depending on location and time of year. Examination of recently published survey data shows that for most gasoline and ethanol blends the $T_{V/L=20}$ falls somewhere within a few degrees of T10 on the distillation curve [9], and so may just be reflective of front end distillation properties. In fact, published data show that $T_{V/L=20}$ and DVPE are inversely well correlated with each other (Figure 1).

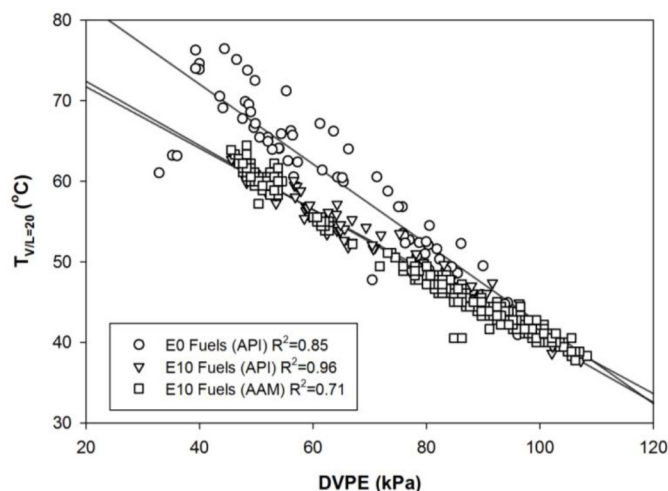


Figure 1. Correlation between DVPE and $T_{V/L=20}$ for E0 and E10 fuels [9,10].

Standards that Assure Adequate Volatility

The T10, T50, and T90 maximums and the Driveability Index (DI) (a calculated combination of T10, T50, and T90), shown in Table 4, were instituted by ASTM standard to ensure that fuel is volatile enough to produce ready starts in cold weather and minimize the potential for unevaporated residue remaining in the fuel system. The DI is currently calculated from equation (1), although this was originally intended only for ethanol concentrations up to 10%, and may be amended to account for higher ethanol concentrations:

$$\begin{aligned} \text{DI } (^\circ\text{C}) = & 1.5(\text{T10}) + 3.0(\text{T50}) \\ & + 1.0(\text{T90}) + 1.33 \times \text{Ethanol Volume\%} \end{aligned} \quad (1)$$

DI equations in degrees Fahrenheit are found in Appendix 2.

Table 4. Standards that ensure adequate volatility in fuel for spark-ignition engines from ASTM D4814-14.

Vapor Pressure/Distillation Class	Distillation Temperatures, °C (°F), at T% Evaporated				Driveability Index, max, °C (°F)
	T10, max	T50, max	T90, max	End Point, max	
AA	70 (158)	121 (250)	190 (374)	225 (437)	597 (1,250)
A	70 (158)	121 (250)	190 (374)	225 (437)	597 (1,250)
B	65 (149)	118 (245)	190 (374)	225 (437)	591 (1,240)
C	60 (140)	116 (240)	185 (365)	225 (437)	586 (1,230)
D	55 (131)	113 (235)	185 (365)	225 (437)	580 (1,220)
E	50 (122)	110 (230)	185 (365)	225 (437)	569 (1,200)

Other properties, not regulated in ASTM D4814, may also affect CWD performance. For example, a 2007 study of eleven cars has shown that an elevated T70 results in worse cold-start and warm-up driveability performance in model year (MY) 2005 to 2007 vehicles in comparison to fuels that have the same DI, but without an elevated T70 [11]. In ASTM-D4814 Appendix XI, the potential for a high T70 due to high levels of reformat (the product of catalytic reforming in a petroleum refinery to produce a high octane, highly aromatic gasoline blendstock) in the gasoline is discussed although no limit is currently in force. The document notes that if T70 is more than 12°C higher than the average of the T50 and T90, it can result in degraded driveability.

Ethanol Effects on Fuel Properties Relevant to Driveability

When 10% ethanol is added to the gasoline, it increases the vapor pressure by about 6.9 kPa (1 psi), lowering its $T_{V/L=20}$ by 5°C to 7°C, and also can lower its T50. Nonetheless, the blend must still meet the requirements of ASTM D4814 to be legal for sale in those states that incorporate the standard in their regulations. However, in much of the United States, the EPA permits E10 blends to have a higher vapor pressure by up to 6.9 kPa (1 psi). In regions where the 1 psi exemption is not in effect, gasoline blendstocks for oxygenate blending (BOBs) have been developed with lower vapor pressure, and make it possible to meet the vapor pressure, distillation and $T_{V/L=20}$ standards.

Distillation curves for gasoline and various ethanol blend levels are shown in Figure 2. Gasoline (in this case, EPA certification gasoline) includes a range of hydrocarbon compounds of varying volatility, such that its distillation curve typically rises steadily as the temperature increases and individual compounds evaporate. The distillation curves of ethanol-containing blends start the same way but then plateau at a relatively constant temperature in the T40 to T60 range as the ethanol and various hydrocarbons distill out of the liquid phase. When the ethanol is evaporated the curve rejoins the distillation curve of the base fuel, thus T10 and T90 are largely unchanged by the addition of ethanol up to 25%.

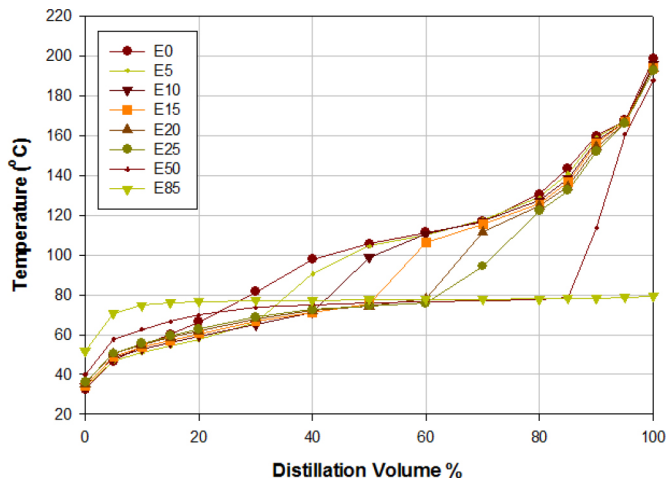


Figure 2. Distillation curves of ethanol in certification gasoline [12].

The T50 of E10 is highly variable because slight differences in the underlying blendstock can result in a T50 very similar to that of most gasolines (about 100°C) (see Figure 3) while other E10s have T50s from significantly below the boiling point of ethanol to slightly above, about 68°C - 80°C. For higher concentrations of ethanol, the length of the ethanol boiling point plateau increases, such that for E15 and higher blends T50 is almost certain to be in this lower range.

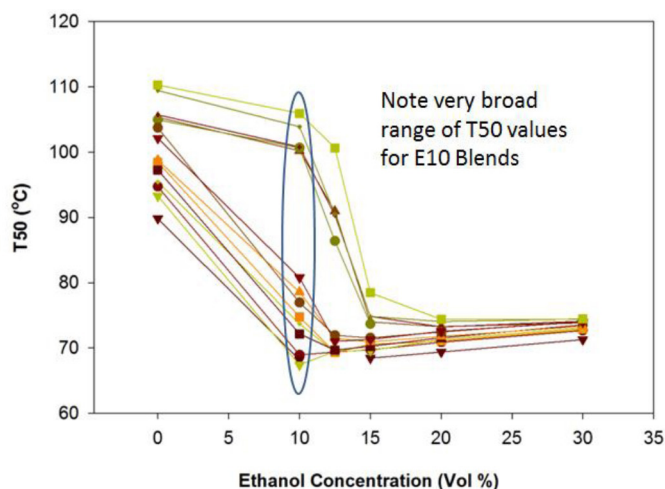


Figure 3. Variation of T50 with increasing ethanol content in Class B and Class C blendstocks [10]. Each line represents a single hydrocarbon blendstock with varying amounts of ethanol added.

Most higher-level ethanol concentration blends (E20+) will have a T50 within several degrees of 70°C. Examples of the wide variety of T50 behavior with varying ethanol content depending upon the base fuel, especially for blends below E15, are shown in Figure 3.

In a cold start, extra fuel beyond the stoichiometric level is added to the cylinder in the first few seconds because only the more volatile fraction of the fuel is expected to evaporate. The amount must be precisely metered to ensure the vehicle starts but does not excessively pollute. Ethanol has a higher heat of vaporization (HOV) than gasoline and thus requires more heat to vaporize readily [13]. Thus more ethanol-blend fuel might be required for a smooth start, in effect, acting like a fuel with a higher T10, T50, or T90. In fact, in the 1980s, European researchers incorporated an estimation of the amount of heat needed to evaporate sufficient fuel to form an ignitable air-fuel-vapor mixture into an equation intended to predict driveability [14]. HOV is not explicitly considered in ASTM D4814; however, the empirically derived ethanol correction factor in the DI equation (equation 1) may embody this effect, along with any other impact of ethanol on CWD.

On the other hand, the higher HOV, by decreasing the temperature in the fuel rail line as fuel evaporates, could conceivably decrease the amount of vapor that forms in hot fuel lines and lessen the potential for vapor lock. However, in a 2000 HWD test a comparison of the average temperature increase over ambient in the fuel rails of vehicles running E10 and E0 showed no measurable difference on average for 11 vehicles [3]. In comparison, the average temperature in the fuel rail for individual vehicles ranged from 75°C to 99°C. Similar results were found in more recent testing of E10 versus E15 (no consistent difference due to fuels in rail line, and more than 28°C difference between the averages of individual vehicles) [15]. This suggests that HOV differences between ethanol and gasoline have no practical effect on the temperature of the rail, and thus no impact on HWD at least up to the E15 blend level.

Ethanol also has a much higher viscosity than gasoline [2] which, at higher blend levels may have a detrimental impact of atomization. Finally, alcohol-containing blends have a lower stoichiometric air/fuel ratio than gasoline, so open loop operation can cause excessively lean operation for engines not properly calibrated for higher alcohol concentrations or not using learned fuel trim to set air/fuel ratio on startup.

DISCUSSION

Driveability Testing Methods

Because modern vehicles have increasingly sophisticated fuel supply systems, recent test programs have found it increasingly difficult to differentiate between the driveability effects of different fuels. Thus, in order to balance between the difficulty and expense of testing large numbers of vehicles and yet ensure that the testing can differentiate between different fuels, many programs conducted in the past decade have involved the selection of vehicles which are particularly sensitive to variations in fuel volatility. For example, a recent CRC study used 20 vehicles selected from 44 originally screened, plus two vehicles added at the request of the manufacturer [16]. Another

included 20 of 85 screened vehicles [5]. A Concawe study used four of eight vehicles screened for cold weather driveability [6]. That these studies are used to determine acceptable fuel properties for the purpose of ASTM D4814 and the like can be justified because fuel formulations are intended to produce acceptable operation in virtually all vehicles, including the most sensitive. However, it should be noted that results collected from these selected vehicles are not considered representative of an average vehicle.

In a CRC study published in 2014 the driveability raters commented that “most laymen could be able to start to feel poor performance greater than the 15-20 demerit level” [17]. In this study of CWD at relatively mild temperatures (2°C to 7°C) and fuels that were within allowable standards or very close, demerit levels ranged from less than 10 to more than 70. Only one vehicle was found to generate fewer than 20 demerits on all fuels, and no fuels were consistently below the 20 demerit level on all vehicles (which were all MY 2011 or newer). The most recent HWD testing done by the CRC employed late model vehicles at a range of temperatures using fuels that had vapor pressures appropriate for the test temperature, and measured demerit levels ranging from 4 to 56 [15]. Roughly one-third of the individual vehicle/fuel tests had more than 20 demerits. If we assume that the level of demerits that feels significant to a typical driver might be about the same for CWD and HWD (and this remains to be confirmed), then both HWD and CWD present some potential for noticeable improvement. However, it should be noted that both of these programs were run on 18 of the more sensitive vehicles, screened from an original fleet of 40.

Within its program, CRC comparisons between raters have shown fairly good correlation. Recent tests have measured a difference of on the order of 10% [18] to 20% [19] between CRC raters, which is acceptable when results can vary by an order of magnitude for different vehicles and fuels. Other testing programs have had more problematic results with repeats differing by as much as a factor of 2 or more, even in cases when only a single rater is used [6].

It has been difficult to isolate the impact of specific fuel parameters on driveability. Gasolines and hydrocarbon blendstocks for blending with alcohols are a complicated mixture of compounds. Altering one property inevitably changes other fuel properties. For example, changing the DVPE typically affects the $T_{V/L=20^\circ}$ and changing the ethanol content changes the DVPE and T50. Where possible, other significant properties are held to a specific range to minimize these impacts.

The combustion air delivered to the engine cylinder is from the ambient atmosphere and thus may vary in temperature, humidity, and in atmospheric pressure. Ambient temperatures are a major factor in testing the effect of gasoline volatility, but are difficult to control and can vary over an unacceptable range. The ambient humidity has rarely been considered, but a recent study found that at least in some vehicles high humidity levels can result in harder cold starts [11], likely because some of the water in the air condenses in the cold engine and then must be vaporized during a cold start, using heat that would otherwise be available for vaporizing fuel. To reduce differences between testing conditions, the CRC has recently developed a test CWD procedure intended for use on a temperature-

controlled indoor chassis dynamometer that could accurately and repeatably control on-road thermal and mechanical loads, although human raters still score the vehicle's operation [20].

Hot Weather Driveability

Fundamental Causes of HWD Issues

The underlying cause of HWD issues is vapor lock, the presence of vapor in sufficient quantities to block adequate flow of fuel to the engine. Supporting this contention is the strong correlation between fuel volatility and demerits in virtually all HWD testing. It is well documented that older carbureted vehicles are more sensitive to fuel properties in warm weather and the reasons are well understood [21]. The fuel supply in carbureted vehicles is under low or negative pressure, as the venturi entrains the fuel into the air/fuel feed to the engine. Under these low pressure conditions, the fuel readily vaporizes in hot weather. Additionally, in older vehicles, the fuel pump was placed outside of the fuel tank, and the intake to the fuel pump was another place in which negative pressure was needed to pull the fuel through the system, and thus potentially the site for vapor lock. In newer cars, the fuel pump is submerged in the fuel tank, and the pump output is pressurized, providing less opportunity for the fuel to vaporize.

Figure 4 shows true fuel vapor pressure of various gasolines and 100% ethanol (E100) as a function of temperature. Note that true vapor pressure differs from Reid vapor pressure (RVP) or its replacement, DVPE [22]. The need for a logarithmic y-axis in Figure 4 underlines how sharply vapor pressures rise with changes in temperature. The addition of ethanol to hydrocarbon fuel at below roughly 40 volume percent (vol%) tends to increase the vapor pressure of the blend relative to E0. Thus, in places where E10 blends are permitted to have a higher vapor pressure than gasoline fuels, they may be more likely to cause problems with vapor lock under hot weather conditions. The relationship between vapor pressure and temperature, derived from the Clausius-Clapeyron equation, is shown in proportionality in equation (2), where P_v is the true vapor pressure, R is the ideal gas constant, and T is the absolute temperature.

$$P_v \propto A e^{-\text{HOV}/RT} \quad (2)$$

Given the proportionality of vapor pressure with $e^{-\text{HOV}/T}$ and because ethanol has a higher HOV than the hydrocarbons in gasoline in the temperature range of interest, the vapor pressure of ethanol blends will be somewhat higher at higher temperatures, such as might occur in fuel lines close to the engine. For example, Tanaka and coworkers measured the vapor pressures of a blend of 3% ethanol in gasoline (E3) and the base gasoline at various temperatures and found that the vapor pressure of E3 was roughly equivalent to the base gasoline at 30°C, higher by 1% to 2% at 40°C, and higher by about 10% at 60°C [23]. To our knowledge, only very limited data on the effect of ethanol blending on the true vapor pressure of gasoline are available in the open literature. However, Tanaka's work suggests it is likely to be significant at the temperatures and ethanol concentrations found in modern vehicle fuel systems.



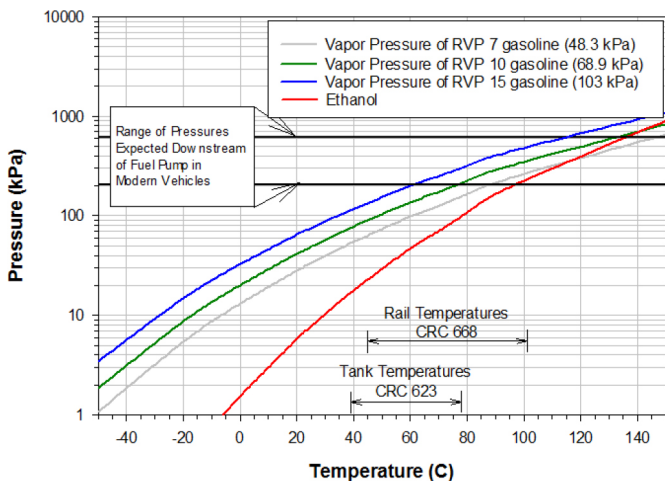


Figure 4. Estimated true vapor pressure of various gasolines in fuel lines compared to pressure in fuel supply lines for hydrocarbon fuels [26]. Also shown are measured rail temperatures (maximum measured over the course of driveability test), and fuel system pressure from mostly MY 2013 and 2014 vehicles in a recent CRC study [15], and fuel tank temperatures from MY1998 and 1999 vehicles from an older CRC study [3].

There has been some consideration of the specific location within the fuel system where vapor lock might occur. Tanimura considers it unlikely that vapor lock would occur in pressurized fuel lines [24]. He suggests that vapor lock remains an issue at the suction inlet to the in-tank fuel pump. A slight vacuum is generated by the pump, on the order of 0.1 kPa below tank pressures according to his measurements. Under the worst case conditions of rapidly rising fuel tank temperatures (perhaps due to an engine under full load), it may be possible for the environment inside of the fuel pump be one of higher temperature and lower pressure than exists in the fuel tank. In addition, Aeromotive, a manufacturer of vehicle fuel pumps, also considers vapor lock at the inlet of the pump a potential issue when the fuel in the tank gets hot, due to the potential for pressure drop between the pump and the tank [25]. If the pressure drop is large, it can result in a greater negative pressure on the fuel that can increase the likelihood of vapor in the fuel at this point.

The pressure in the fuel tank varies with heating and cooling over the day, but the tank is vented through a carbon canister that keeps pressure close to atmospheric and the liquid in equilibrium with the vapors in the tank. At the intake to a fuel pump in the fuel tank, the pressure will be roughly that of the pressure in the tank plus the pressure due to the height of the fuel in the tank minus any pressure drop due to fixtures or filters between the fuel pump and the tank. Two centimeters of fuel exerts more than 0.1 kPa of pressure head. The effect will be small, but a few centimeters of fuel would seem likely adequate to offset any intake pressure drop for pumps located directly next to or inside the fuel tank.

Also shown in Figure 4 is the range of fuel system pressure that might be encountered downstream of the fuel pump from the fuel tank, ranging from about 138 kPa up to 620 kPa. To prevent vapor lock, the fuel line is shielded from engine heat to the extent possible, the fuel supply lines are pressurized as practicable, and the vapor pressure in fuels is controlled. In 1999, the CRC measured fuel rail temperatures of 11 vehicles during driveability testing under hot

ambient conditions (27°C to 38°C) and found temperatures ranging from about 71 to 96°C [3]. This is consistent with the fact that the engine thermostat typically maintains the coolant temperature at about 95°C, giving an approximate upper limit to the temperature that might be reached in the fuel line. Fuel tank temperatures were lower, between 38°C and 77°C. CRC researchers found that these internal vehicle temperatures were correlated with ambient conditions. In more recent testing over a wider range of ambient temperatures (from 18°C to 39°C), the CRC reported a greater range of rail temperatures (46°C to 102°C) [15]. Measured fuel system temperatures are also shown in Figure 4. The graph suggests that fuel is commonly at temperatures where the vapor pressure is greater than the system pressure; hence, there is potential for vapor lock.

It is not clear at what ratio of fuel vapor pressure to fuel system pressure that vapor lock becomes problematic, but this has typically been addressed as an allowable temperature at which the V/L ratio reaches a certain level. Since 1970 and the promulgation of ASTM D439, the volumetric ratio of 20 to 1 has been the standard due to the results reported in [8].

In 2000, the CRC found evidence that HWD demerits were better correlated with a property called $T_{V/L=1,500}$, the temperature at which the vapor-to-liquid volumetric ratio is 1:1 at a pressure of 500 kPa (72 psi), than with the temperature at which vapor-to-liquid ratio was 1 at lower pressures down to 100 kPa (roughly atmospheric) [3]. Five hundred kPa is within the range of injection operating pressures in modern PFI vehicles, and the report states that the one-to-one ratio is considered approximate to that which will prevent fuel injectors from supplying the required fuel to the engines. Thus, this correlation suggests that the primary site for vapor lock is in the fuel rail or injector. However, in several programs since that time the correlation has not held up [5,16,19]. Moreover, in more recent testing on MY 2013 and 2014 vehicles, the CRC found that higher fuel rail pressures were correlated with worse HWD performance (p-value = 0.01), although the coefficient was small [15], suggesting that further increases in pump pressure will not improve HWD performance. Higher rail temperatures were associated with higher demerits and with higher tank temperatures [3,15].

Correlation of Fuel Properties and HWD Vehicle Test Demerits

The CRC and others have conducted numerous tests to evaluate HWD in the past 25 years, many studies explicitly designed to determine appropriate fuel quality standards. These are listed in Appendix 3, and the results of several notable studies are described here. In 1993, the CRC conducted an investigation of the effects of T50 on HWD performance of vehicles ranging in from MY 1983 to MY 1992, including both carbureted and fuel-injected systems [27]. Fuels used included hydrocarbon gasoline, E10, and 15vol% methyl tert-butyl ether (MTBE) in gasoline. T50s varied from 61.7°C to 90.6°C. Ambient temperatures ranged from the about 20°C to over 38°C. It found the level of driveability demerits was about three times higher for carbureted vehicles relative to PFI. For the carbureted vehicles, decreasing T50 caused a small but statistically