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EVALUATING THE DRIVEABILITY INDEX RELEVANCE IN MODERN GASOLINES AND VEHICLES

Final Report

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COORDINATING RESEARCH COUNCIL, INC.

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Abstract

The regulation of gasoline standards is essential for ensuring the proper operation of a spark ignition (SI) internal combustion (IC) engine. Over the past many decades, automotive companies and fuel manufacturers have collaborated to develop appropriate gasoline volatility standards that will ensure the smooth operation of vehicles in cold and hot weather conditions, while maintaining the practicality of blending at the refineries. Inadequate low-temperature fuel volatility can cause operational issues during cold start and warm-up operation. The Driveability Index (DI) was an index developed in the 1980s to ensure gasoline in the United States has adequate volatility through all seasons for every region in the country. DI is calculated using gasoline distillation temperatures T10, T50, and T90, and has an additional term for ethanol-gasoline blends based on the quantity of ethanol added to gasoline.

Driveability Index limits on different volatility classes of gasoline are specified in the ASTM D4814 standard. Over the years, DI has played an important role in ensuring smooth driveability in a large country with a multitude of different climate zones. However, the model used to calculate DI was developed over 35 years ago using data from vehicles and fuel systems representative of that era. In the interim, there have been significant developments in SI engines and engine control systems, which have fundamentally changed the way engines respond to fuel volatility. There have also been dramatic changes in emissions regulations for tailpipe and evaporative emissions, both of which are influenced by fuel volatility. Additional factors such as stochastic pre-ignition (SPI) and particulate matter (PM) emissions have gained importance and also show sensitivity to fuel volatility. These changes raise the question – **Is Driveability Index relevant for modern gasoline engines and vehicles, or is it an artifact of the past? And, if volatility control is still important, is the current DI formula and associated specifications still the correct way to control it?**

This report provides a comprehensive review of the available literature and in-depth interviews with topical experts on the subject, including driveability, fuel volatility properties, and the history of the Driveability Index. Findings from driveability studies conducted by the Coordinating Research Council (CRC) and other research organizations are summarized in the context of DI. This work also evaluates fuel volatility specifications from the United States, the European Union (EU), Japan and China. Properties of gasoline samples collected from the four regions are analyzed to investigate regional approaches for ensuring smooth driveability. Interviews conducted with subject matter experts (SMEs) from the automotive and fuel industry alike are included in the analysis to bolster claims.

The analysis shows that although the importance of volatility may have shifted based on the updates to technology and emission standards, modern vehicles remain sensitive to fuel

volatility. While gasoline volatility control is still an important requirement, the data suggests there may be alternative metrics and limits that could provide adequate protection for good driveability while better capturing the effects of ethanol and easing constraints on gasoline refining. The report culminates with recommendations for future work to identify improved metrics and confirm the impact of modern vehicle technology on gasoline volatility sensitivity.

Introduction

The automotive industry is over a century old. In that time, the automobile has become an important variable in the equation for technological development, improvement in the quality of life, and bringing the world closer. Over the years, the internal combustion (IC) engine, as well as automobiles, have seen significant improvements with regards to efficiency and reduction in tailpipe emissions.

The majority of the advancements that the automotive industry has seen in the past many decades – especially for the IC engine – have gone hand in hand with improvements in fuel quality. Charles Kettering, who was a pioneer and a highly influential figure in the US automotive industry in the early 1900s, said "The automotive industry was considered a mechanical one until fuel difficulties caused a realization that the internal combustion engine is only a piece of apparatus for the effective utilization of chemistry" [1]. Since the 1920s, like the automotive industry, fuel specifications have undergone a plethora of changes. But fuel volatility gained added importance due to the Clean Air Act (CAA) of 1963 [2], and amendments to it after the establishment of the Environmental Protection Agency (EPA) in 1970. The CAA introduced cold start emission standards which limited the permissible level of cold start enrichment and resulted in the deterioration of cold start driveability [3]. To comply with the new regulations, engines were modified to reduce exhaust emissions, which negatively impacted fuel economy and driveability in MY 1970 to MY 1972 vehicles [4].

The change in emission regulations set into motion extensive research and investigations into the importance of fuel volatility on vehicle driveability and emissions conducted by the Coordinating Research Council (CRC) Inc., original equipment manufacturers (OEMs), and the oil companies. The effort culminated in the establishment of the Driveability Index (DI) in the United States, which has been a part of the ASTM[1] D4814 standard since the year 1998. DI is a parameter used to ensure the fuel has the required level of volatility across the distillation range. DI is calculated using three distillation temperatures of the fuel (T10, T50, and T90) and has the units of temperature (typically expressed as °C or °F). The current DI equation in the most recently updated version of the ASTM D4814 standard (ASTM D4814-25[2]) [5] is shown below.

[1] ASTM – American Society of Testing and Materials

[2] The '-25' after 'ASTM D4814' refers to the year the update was made. In this case, it refers to the version of the standard updated in 2025.

Equation 1a shows the DI equation for fuel blends containing 0% to 10% ethanol by volume with the distillation temperatures in °C, and Equation 1b shows the same equation for distillation temperatures in °F.

Driveability Index (°C) = 1.5×T10 + 3.0×T50 + 1.0×T90 + 1.33×(%Ethanol by volume) (1a)

Driveability Index (°F) = 1.5×T10 + 3.0×T50 + 1.0×T90 + 2.4×(%Ethanol by volume) (1b)

Where:

T10 – Temperature at which 10% of the fuel has evaporated as measured using ASTM D86
T50 – Temperature at which 50% of the fuel has evaporated as measured using ASTM D86
T90 – Temperature at which 90% of the fuel has evaporated as measured using ASTM D86

Equation 2a shows the DI equation for fuel blends containing greater than 10% and up to and including 15% ethanol by volume with the distillation temperatures in °C, and Equation 2b shows the same equation for distillation temperatures in °F.

Driveability Index (°C) = 1.5×T10 + 3.0×T50 + 1.0×T90 + (1.33 + [(%Ethanol by volume-10)/5)]×(5.26-1.33))×(%Ethanol by volume) (2a)

Driveability Index (°F) = 1.5×T10 + 3.0×T50 + 1.0×T90 + (2.4 + [(%Ethanol by volume-10)/5)]×(9.49-2.4))×(%Ethanol by volume) (2b)

Since the addition of DI limits to the ASTM D4814 standard in the year 1998, the equation to calculate DI has evolved to address the effects of ethanol on gasoline in the United States, along with a few minor changes to the verbiage in the standard. During that time, there have been significant advances in vehicle technology as well, especially with regards to high pressure gasoline direct injection (GDI) fuel systems, closed-loop control systems, and a variety of valve control technologies. Tier 1 emission standards were in place in the early 2000s, which have since advanced to Tier 3 in 2017, with Tier 4 emission standards on the horizon starting with MY 2027 vehicles. These shifts have had an impact on the sensitivity of modern vehicles to fuel volatility. This report provides an in-depth analysis of the evolution in fuel standards, engine and vehicle technology, emission regulations, and evaluates

whether Driveability Index, as it is currently defined, remains the appropriate metric for ensuring acceptable cold start and warm-up driveability in modern vehicles.

Figure 1 shows the timeline for all relevant events that have impacted fuel volatility standards, the conception of DI, vehicle technology updates, and emission regulations.

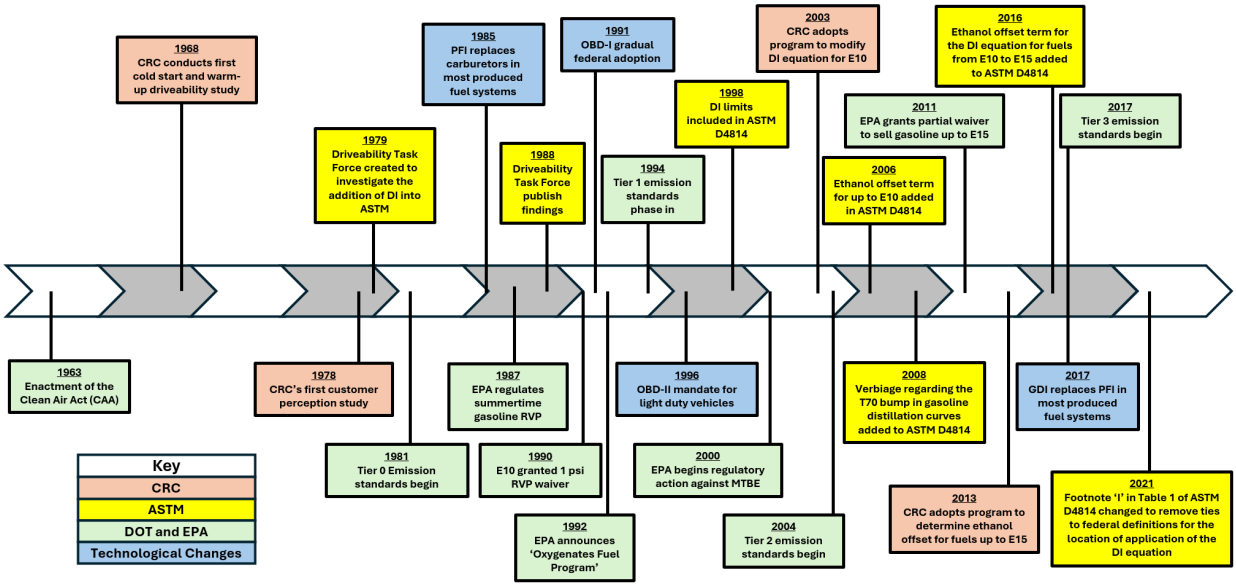


Figure 1: Timeline of events related to Driveability Index, SI engine fuel systems and emissions regulations

Executive Summary of Findings and Recommendations

The thorough review of the literature on cold start and warm-up driveability and DI, coupled with interviews conducted with SMEs from the automotive industry, fuel industry, and regulatory entities, points to the fact that gasoline volatility continues to be an important parameter for the proper operation of gasoline SI engines, which is consistent with the most recent driveability study conducted by the CRC [6]. The upgrades in engine technology and control systems to accommodate variable volatility fuel have been at least partially balanced out by more stringent emission regulations, meaning modern vehicles are not decoupled from fuel volatility. Whether Driveability Index is still the best model to correlate fuel volatility to cold start and warm-up driveability remains to be seen. The data available is insufficient to draw a conclusion on whether DI can be improved upon or replaced by another metric. However, there are no indicators that DI has been rendered irrelevant in modern vehicles. The available data suggests that Driveability Index remains a relevant parameter for modern gasolines and vehicles to ensure smooth driveability while also adhering to emissions standards. Based on this, the findings and recommendations of this report are summarized below.

- A thorough review of advances in internal combustion engine technology and the potential interactions with fuel volatility was conducted. The impact of modern engine technology on sensitivity to fuel volatility metrics such as DI is complex with both benefits and detriments in many cases. In theory, technologies such as gasoline direct injection (GDI) would allow modern vehicles to tolerate fuels with higher DI than in the past. These benefits are counteracted – at least partially – by increasingly stringent emissions regulations that limit the amount of enrichment that is permissible.
- This study concludes that a controllable proxy for in-use fuel volatility remains an important parameter. However, the available literature is not sufficient to determine if the existing calculated parameter – Driveability Index – is the optimal proxy for modern engines. Additional experimental testing needs to be conducted to determine the relevance of DI in modern vehicles (vehicles with downsized and turbocharged engines with a high pressure GDI fuel system and variable valve timing (VVT)). The last three decades of the 1900s saw a plethora of driveability studies conducted by the CRC and OEMs. Driveability studies have dwindled in the last two decades, with the last study involving trained raters conducted in 2014 [7]. A comprehensive driveability study involving modern vehicle performance, emissions standards, and realistic drive cycles will be necessary to draw a concrete conclusion on whether DI has been rendered irrelevant by modern technology.

- Based on discussions with SMEs, there is interest in moving away from the subjective rater-based demerits system to an objective sensor-based system to determine total weighted demerits (TWDs). The trained rater system proved useful in the past, but multiple studies have reported a lot of variability between trained raters, which can be eliminated by objective metrics. The shift to objective metrics would enable a fairer comparison across driveability studies. To make the shift, it is important to gauge the correlation between demerits experienced by the average customer and those detected by sensors. The last customer perception study adopted by the CRC was conducted in 1993 [8]. A customer perception study conducted with modern vehicles will be an important step to determine the relevance of fuel volatility and Driveability Index.
- The impact of the addition of ethanol on driveability requires additional investigation. CRC studies were conducted to update the DI equations for ethanol-gasoline blends up to E10 [9], and ethanol gasoline blends from E10 to E20 [10], which have shown that the coefficient for the correction factor depends on the percentage of ethanol by volume, and serves more of a superficial correction on underlying causes. The impact of the base hydrocarbon blend – which is the makeup of the blendstock for oxygenate blending (BOB) – on the ethanol correction factor needs to be investigated. If a clear consensus to predict driveability issues using distillation temperatures cannot be reached, alternative approaches like the use of vapor pressure, lower explosive limit (LEL), or heat of vaporization (HoV) could be considered [11]. Another approach could be to regulate the base fuel, irrespective of the amount of ethanol that could be added to the gasoline. But this approach is uncertain due to the non-linear effects on volatility from ethanol when blended into hydrocarbon gasoline.
- Analysis of vehicle adaptive systems and emissions: Previous studies provided insight that some modern vehicle control systems have the capability to detect driveability issues and adaptively modify the calibration to compensate for changes in fuel volatility. A test program to assess the range of capabilities of this adaptive control technology and any impacts on vehicle emissions or other aspects of vehicle performance is recommended.
- This study conducted a comparative analysis of gasoline volatility requirements from the United States (US), the European Union (EU), Japan, and China, which constitute four of the five major global automotive markets. Comparison between the volatility requirements showed that the three other regions do not have a parameter analogous to the Driveability Index and use either distillation temperatures or evaporative limits along with the final boiling point (FBP) and vapor pressure to control and monitor gasoline volatility.

- Investigation of gasoline samples from each of the four regions mentioned above, based on fuel surveys conducted by SGS INSPIRE [12], highlights the fact that even though there are differences in the volatility requirements of the regions, all samples from summer and winter of 2024 adhere to the DI requirements of the ASTM D4814 specification[3]. With minor exceptions, the median DI gasoline samples from the EU, Japan, and China, show conformance with the US volatility requirements, and vice versa. This mutual conformance suggests that gasoline volatility properties are driven by vehicle performance and emission regulations.

[3] It should be noted that the EU, Japan and China do not have a Driveability Index requirement. The DI of samples from each region was calculated using distillation temperatures and the percentage of ethanol by volume for the purposes of the comparative analysis.

Driveability and the History of the Driveability Index (DI)

Before the Driveability Index equation was recommended by the taskforce created by ASTM Subcommittee D02.A on gasoline, there were multiple equations proposed and used by OEMs for their internal research that related vehicle driveability to fuel volatility parameters. After the recommendation and eventual institution of Driveability Index in ASTM D4814-98a, there were multiple changes made to the equation as well as the specification. The technological road from the late 1960s to the present has been a fascinating one. An important part has been the effort to maintain good vehicle driveability and keep customers satisfied. But before we take a stroll – or more accurately, a drive – through the history of the Driveability Index, a question needs to be addressed – What is driveability?

Driveability

Driveability is the quality of power delivery from a vehicle's engine to its wheels as determined and demanded by the driver. In the ideal scenario, this delivery of power is smooth, predictable, and without hesitation, which is what customers desire and perceive as good driveability. Deterioration in driveability can be felt through vehicle and engine performance issues such as stalls, idle roughness, backfires, hesitation, stumbles, and surge. These issues, as CRC studies state [13, 14], can be defined as follows:

a) **Stall – Any occasion when the engine stops with the ignition on. Stalls can be further divided into three types.**
    1. **Idle Stall – Any stall experienced when the vehicle is not in motion, or when a maneuver is not being attempted.**
    2. **Maneuvering Stall – Any stall experienced when the driver attempts to move or stop the vehicle or while the vehicle is in motion.**
    3. **Decelerating Stall – Any stall which occurs while decelerating between maneuvers.**
b) **Idle Roughness – Vehicle smoothness while the engine is idling.**
c) **Backfire – An explosion in the induction or exhaust system.**
d) **Hesitation – A temporary lack of initial response to changes in throttle position.**
e) **Stumble – A short, sharp reduction in acceleration rate experienced under acceleration or road load conditions.**
f) **Surge – A continued or transient condition of fluctuations in power, experienced as changes in acceleration rate which are short or long, cyclic or random, and occurring at any speed and/or load.**

These phenomena are often related to in-cylinder air-fuel ratio deviations causing torque fluctuations and misfires.

Driveability is impacted by gearing, handling, steering traits, powertrain isolation, etc. [11], but a prominent factor impacting driveability is fuel volatility. Fuel volatility issues can lead to unacceptable cold weather driveability (CWD) as well as hot weather driveability (HWD).

- In cold weather, a lack of fuel volatility – particularly insufficient light end components – can lead to difficulty in cold start and warm-up.
- In hot weather, higher fuel volatility – particularly high vapor pressure or $T_{V/L=20}$ – can lead to vapor lock issues, although with the fuel systems progressing from carbureted to the current mix of port fuel injection (PFI) and gasoline direct injection (GDI) fuel systems, there has been a significant mitigation of vapor lock issues.

Driveability is a perceived phenomenon, meaning it is subjective, and its perception changes from person to person. To quantify driveability issues, the CRC created a demerit system, which is a numerical score assigned to the severity rating of a malfunction. The CRC assigned trained raters for driveability testing programs to operate the vehicles in the programs [13, 14]. The trained raters assigned demerits in performance to each vehicle when testing a particular fuel. The total weighted demerits (TWD) were the sum of demerits assigned to all malfunctions observed during a test run, each multiplied by a weighting factor based on the relative importance assigned to that malfunction. TWD was a number used in multiple driveability models and was a basis for the existing DI formula. The demerit criteria used in CRC driveability studies is shown in Table 1.

Table 1: CRC demerit criteria for driveability studies [15]

Malfunction	Rating	Demerit(s)
Start Time	Seconds	5 × (Seconds - 1)
Rough Idle	Clear	0
	Trace	1
	Medium	2
	Heavy	4
	Extreme	8
Stall in Park	Count	10 × Count
Stall in Drive	Count	16 × Count
No Start (3 maximum)	Count	32 × Count
Unable to Start or Operate After Numerous Attempts		192[1]
Driving Malfunctions[2]	Clear	0
	Trace	4
	Medium	8
	Heavy	16
	Extreme	32
	Small	64

[1] Maximum demerit rating; excludes all other malfunction demerits for that individual soak cycle; equivalent to three driving stalls.
[2] Includes hesitation, stumble, surge and backfire.

History of the Driveability Index (DI)

The Driveability Index (DI) is related to cold start and warm-up driveability of a vehicle. The bulk of the work on cold start driveability began in the late 1960s, after the promulgation of the Clean Air Act of 1963. Prior to that, the majority of studies on fuel volatility focused on the issue of vapor lock, an example of which is CRC Report 403 [16]. IC engines used in automobiles underwent design and calibration changes to meet the new emission regulations, but the changes came with the undesired effects such as misfires and loss of power, especially in cold weather where the amount of fuel that evaporates is lower as compared to warmer weather [17]. One of the solutions for mitigating these problems was making changes to the gasoline composition, which is why driveability programs gained a lot of traction during that period.

CRC Driveability Testing (1969 – 1972)

In 1968, the CRC Motor Volatility Group adopted a program to develop driveability procedures and to evaluate the effect of fuel volatility on driveability at different ambient temperatures. The program consisted of three phases.

1. Driveability Evaluation in Cool Weather – 1969 (Pasco, Washington) (CRC Report 439)
2. Evaluation of High Temperature Driveability Test Procedure – 1971 (Yuma, Arizona) (CRC Report 455)
3. Intermediate Temperature Driveability Program – 1972 (Camp Roberts, California) (CRC Report 483)

The primary objective of this program was to develop a procedure for evaluating vehicle driveability to assess the impact of fuel volatility.

Phase 1 of this program, which took place in Pasco Washington, tested 16 cars with 4 fuels. Two of the fuels had a T50 of approximately 190°C (374°F) and the other two had a T50 of approximately 230°C (446°F). One fuel from each pair had Reid Vapor Pressures (RVP) of 6 psi and 9 psi, respectively. The distillation curves for the four fuels are shown in Figure 2.

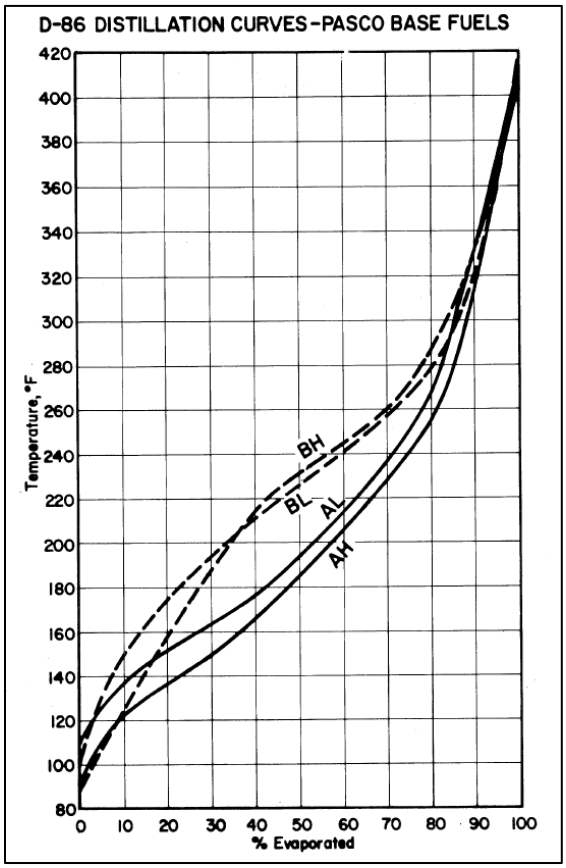


Figure 2: Distillation curves of fuels used in the CRC 439 study [13]

The procedure used in CRC driveability programs is included in the Appendix.

This study developed one of the first driveability models or metrics for fuel volatility. The results showed that cold start and driveaway driveability were not affected by the RVP of the fuel, but rather showed a correlation with:

- Sum of percents evaporated at 130°F, 150°F, 190°F, and 250°F
- Sum of half of T10 and T50

This is shown through Equation 3a and 3b.

$$\mathbf{TWD \propto (E130+E150+E190+E250) \quad (3a)}$$

$$\mathbf{TWD \propto (0.5xT10 + T50) \quad (3b)}$$

In Equation 3a, 'E130' represents the percentage of the fuel that has evaporated at 130°F (and the same for other temperatures).

The cold weather and intermediate weather testing were in agreement that cold start and warm-up driving were impacted by fuel volatility. Both studies, however, mentioned that the recorded demerits did not include surge and idle roughness, which is to say these issues were not impacted by fuel volatility. Warmed-up [4] driveability was not impacted by fuel volatility for the test procedure used.

The intermediate temperature driveability program correlated the demerits with driveability models that included T90. This was a change from Equation 3b from Phase I of the project, which correlated total weighted merits to only T10 and T50. Multiple equations were included in the report. Equation 4 shows the model for the correlation of adjusted demerits with T10, T50, and T90 for production cars (excluding two cars). The term 'adjusted demerits' refers to total weighted demerits (TWDs) corrected for rater bias and the day-to-day variation.

$$\mathbf{Adjusted\ Demerits\ (°F) = 0.62xT10 + 0.85xT50 + 0.47xT90 - 286 \quad (4)}$$

All phases showed that there were large differences between raters. Like the fuel volatility, the raters were a variable in the equation.

[4] Warm-up driveability and warmed-up driveability should not be confused with each other. Warm-up driveability is when the engine is warming up. Warmed-up driveability is when the engine is already warmed up.

Independent Company Studies (1970s)

In the early 1970s, multiple companies conducted independent studies and developed their own driveability models. P. Clarke from Esso Research and Engineering company introduced the Warm-Up Index (WUI) in his study published in 1971 [3]. Clarke mentioned the importance of the fuel providing smooth driveability and preventing knock while maintaining emissions below the required levels, and that volatility played an important role in the equation to solve this problem. The WUI introduced in [3] is shown in Equation 5.

$$\textbf{Warm-up Index (WUI) (°F)} = \textbf{(E212)} + \textbf{(E302)} \quad \textbf{(5)}$$

The WUI model displayed reasonable agreement with the CRC program from 1969. In subsequent work published in 1972 [18], Clarke modified the equation and renamed it to Driveability Index (DI), which is shown in Equation 6.

$$\textbf{Driveability Index (DI) (°F)} = \textbf{(E212)} + 0.5 \times \textbf{(E302)} \quad \textbf{(6)}$$

The study also included a model for Vapor Lock Index (VLI), shown in Equation 7.

$$\textbf{Vapor Lock Index (VLI) (°F)} = \textbf{RVP} + 0.13 \times \textbf{(E158)} \quad \textbf{(7)}$$

In 1974, J. Ingamells introduced a model based on internal data from Chevron Research Co. [4]. The model, termed 'Volatility Factor', consisted of front-end, mid-range, and back-end volatility in the form of T10, T50, and T90. The model is shown in Equation 8.

$$\textbf{Volatility Factor (°C and °F)} = 0.5 \times \textbf{T10} + 1 \times \textbf{T50} + 0.5 \times \textbf{T90} \quad \textbf{(8)}$$

This model was similar to the one published by the CRC cold weather study in 1969, but had the additional component of T90. The results from Ingamells' study are shown in Figure 3. Within the range of volatility factors tested, the TWD value does not increase significantly up to a volatility factor of 430°F (221.1°C). When the Volatility factor exceeds that, which would mean heavier hydrocarbons in the fuel blend, the cold starts demerits increase for MY 1970 and MY 1972 vehicles. Warmed-up driveability was unaffected by fuel volatility based on this data. This is potentially due to the fact that the demerits in warmed-up driving occurred for high volatility fuels with volatility factors lower than the minimum value shown on the graph below.

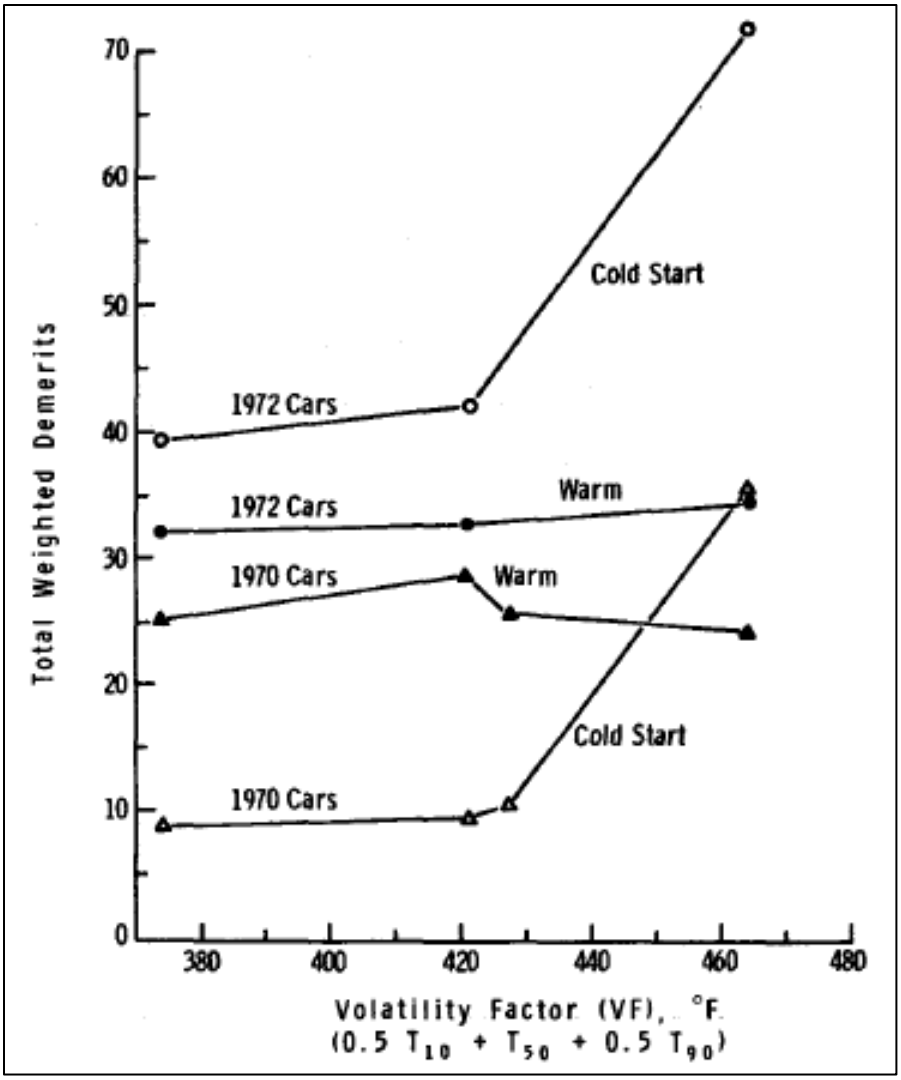


Figure 3: TWDs as a function of Volatility Factor for MY1970 and MY 1972 cars [4]

The results from this study were also compared with other programs, including data from the 1972 CRC program, which is shown in Figure 4. Although the test procedures – and hence the magnitude of TWD - were different, the trends were comparable and corroborated the findings from Chevron's study. Figure 4 shows that the performance deteriorated as model years progress, reflecting the reduced enrichment required to meet emissions standards.

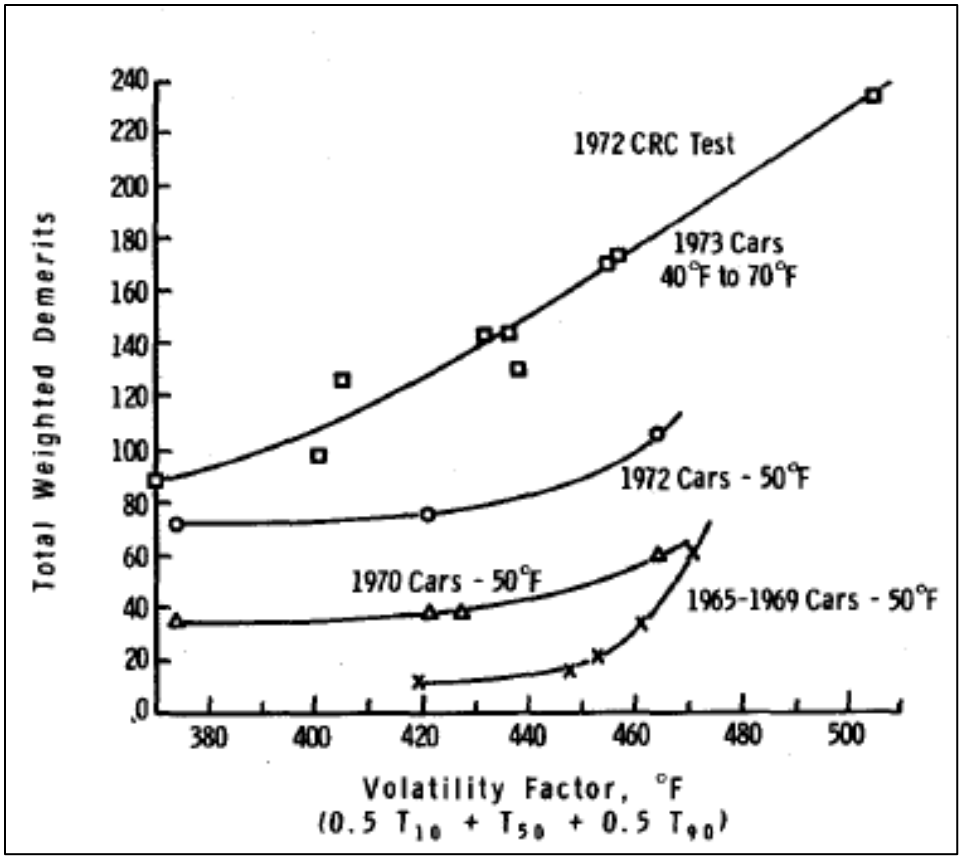


Figure 4: TWDs as a function of Volatility Factor for multiple studies [4]

It is interesting to note that the majority of driveability models developed from the early studies on driveability recognized the importance of mid fuel volatility in their data, seeing as the coefficient for T50 influence was greater than the other distillation temperatures.

CRC Driveability Studies (1973 – 1977)

The Motor Volatility Group at CRC continued their work on the impact of fuel volatility on driveability with additional ambient temperature tests carried out in 1975 [19] and 1977 [20] for passenger vehicles, the experimental work for both of which was conducted in California. For MY 1975 and MY 1977 cars, the data showed that driveability demerits at intermediate temperatures decreased with an increase in fuel volatility. The study involving MY 1975 cars stated in its conclusion that the 50% distillation point (T50) had the greatest impact on driveability demerits, followed by 10% distillation point (T10) with the 90% distillation point (T90) having the least impact of the three values. The study included 9 test fuels with two values for each of the three distillation temperatures of interest (T10, T50 and T90). The fuel

design for the 9 fuels for the variation in distillation temperatures is shown in Figure 5. Based on the calculated combination of fuels, the program was able to decipher the prominence of each of the three distillation temperatures on driveability and demerits.

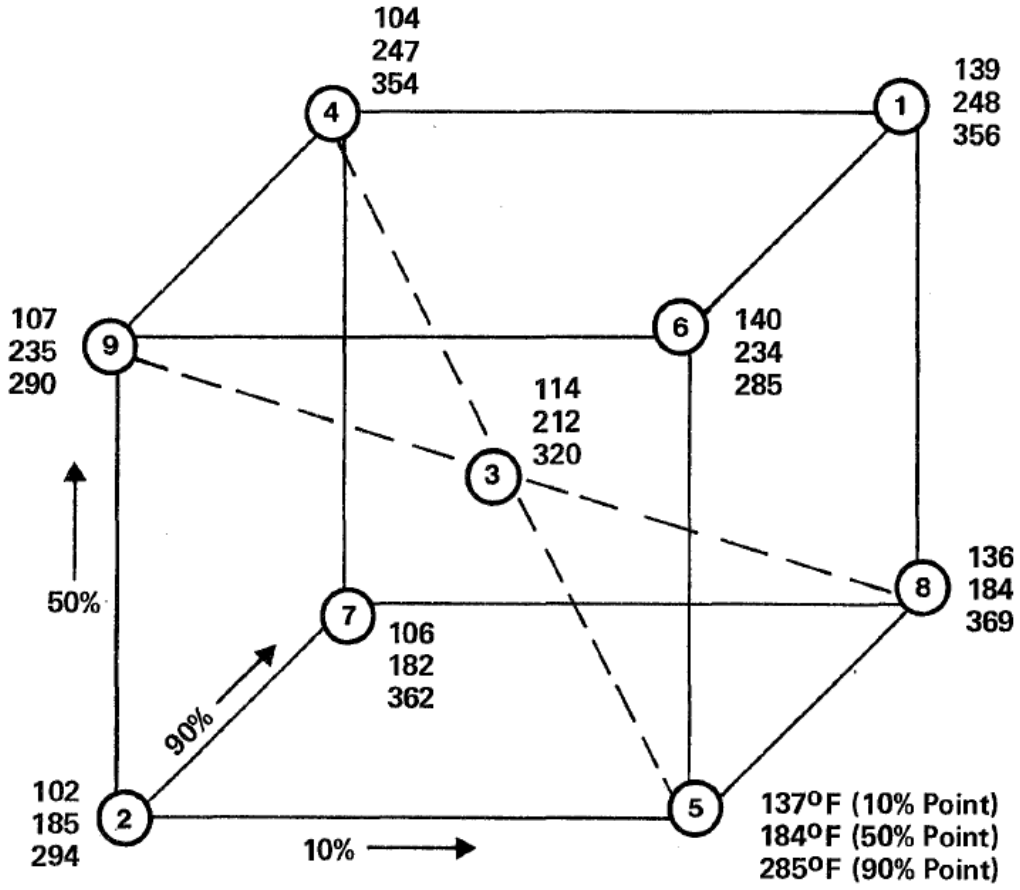


Figure 5: Fuel design for fuels used in CRC 486 [19]

Equation 4, which was the equation for driveability demerits developed in the 1972 CRC intermediate temperature study [14] was in good agreement with 1975 vehicles as well.

The 1977 study, which was Phase Two of the same program, focused more on vehicles rather than fuels. The results of phase two were in agreement with previous studies where decreasing the fuel volatility increased driveability demerits. Figure 6 shows the distribution of average adjusted TWDs for all cars. The average TWDs decreased with an increase in fuel volatility. All cars recorded the highest demerits for the low volatility fuel, while 90% of the vehicles in the program (36 out of 40) had higher demerits for the intermediate volatility fuel

as compared to the high volatility fuel. Only 10% of the vehicles in the program (4 out of 40) deviated from the trend showing higher demerits for the high volatility fuel than the intermediate volatility fuel.

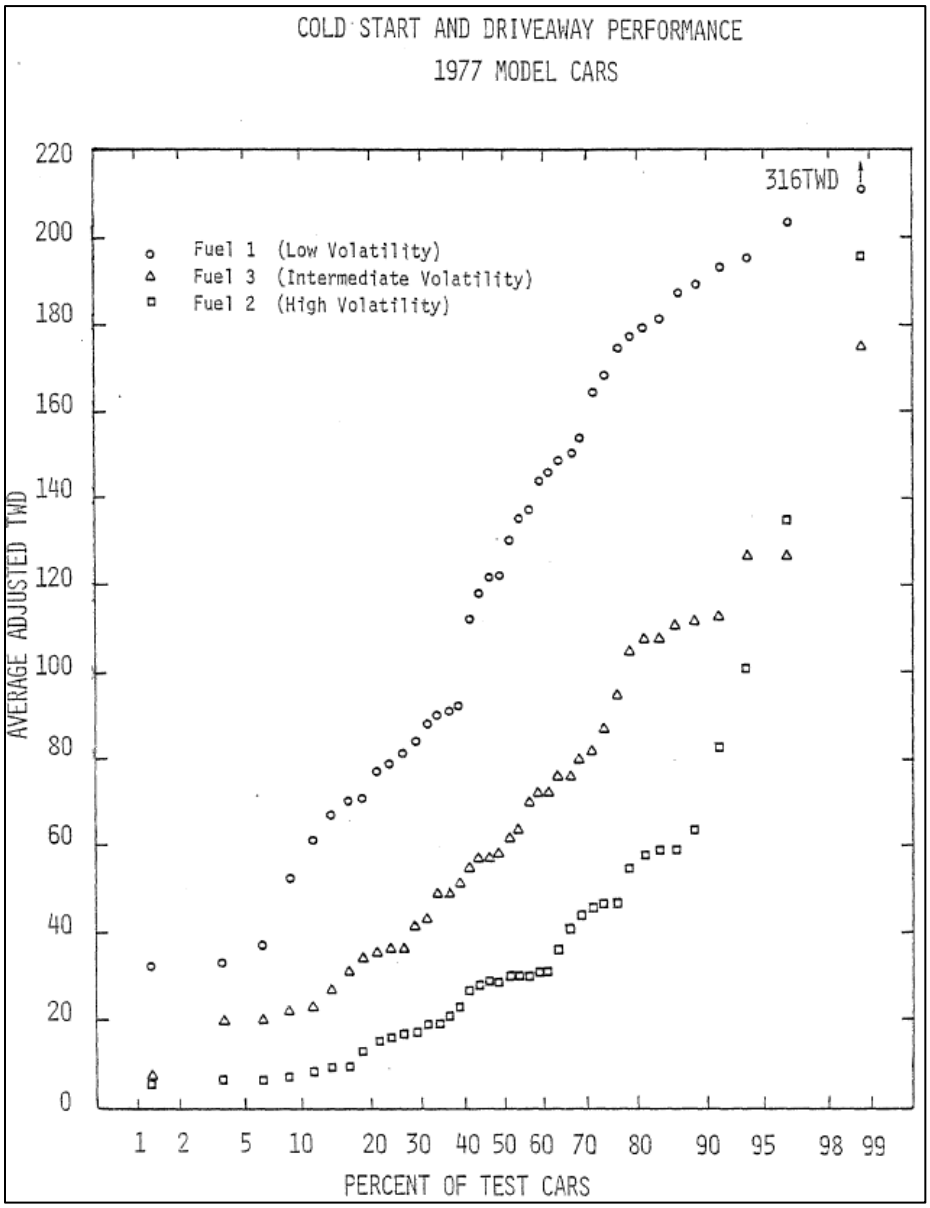


Figure 6: Variation of TWDs with fuel volatility [20]

With one minor exception, the same test procedure was used in evaluating the driveability quality of all three car fleets (1973, 1975, and 1977) tested at Paso Robles. The exception was that the starting procedure was varied to reflect changes in the car manufacturers' starting recommendations. The variation in demerit level due to these changes was considered minor in view of the overall total demerits for each test run. Figure 7 shows the comparison of MY 1973, MY 1975 and MY 1977 cars using Equation 4. The graph shows that

driveability issues for the same fuel volatility reduced for later years as vehicle manufacturers implemented solutions to counter poor driveability. However, the graph also tells the story that MY 1977 cars were dependent on fuel volatility just like their predecessors, and TWDs increased with decreasing fuel volatility.

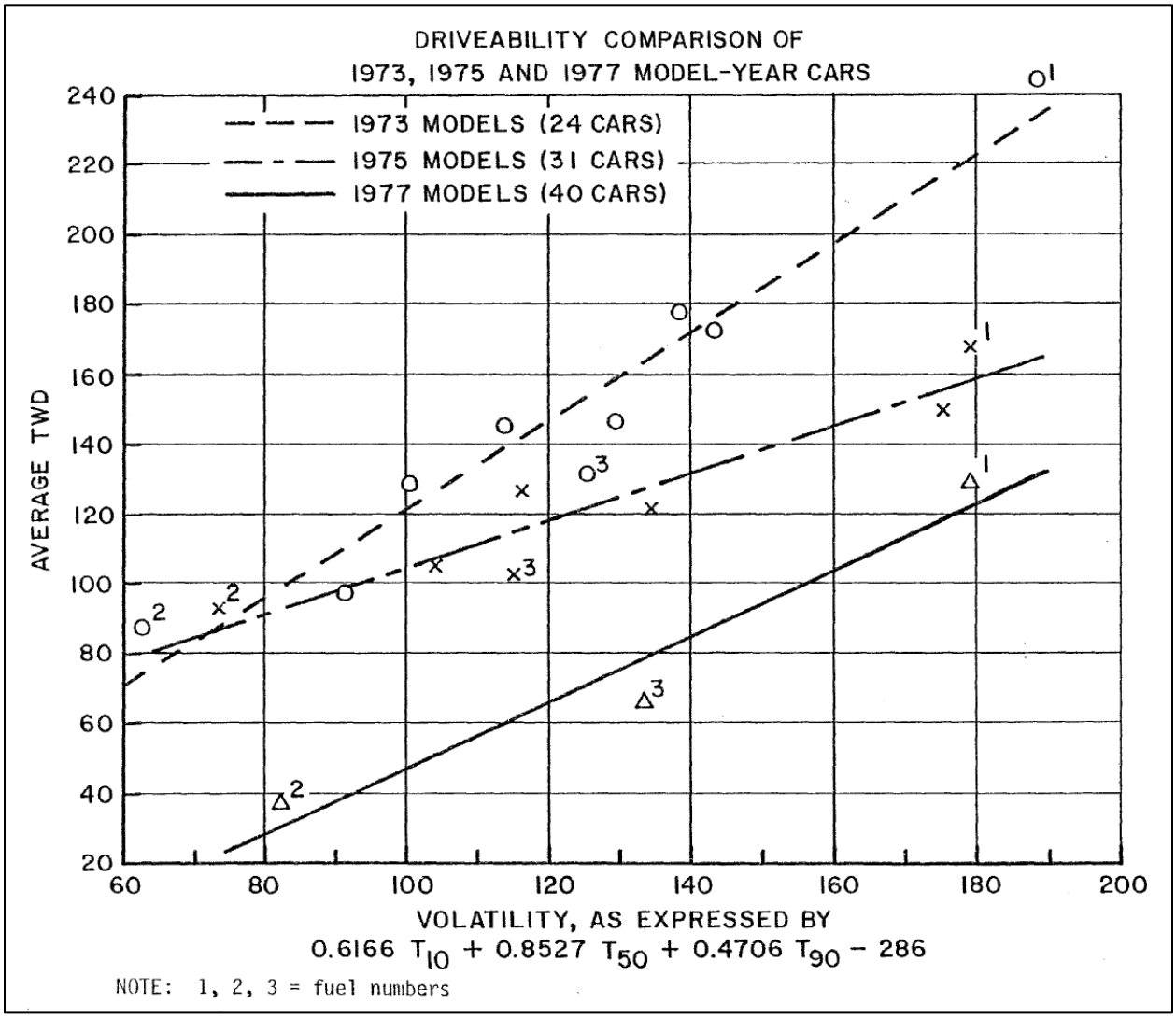


Figure 7: TWDs of MY 1973, MY 1975 and MY 1977 cars as a function of the driveability model developed in CRC Study 499 [20]

CRC Customer Perception Study - 1978

All CRC programs used trained raters to recognize and evaluate driveability issues and demerits. But it was important to know whether the average customer's perception trended in the same direction as the CRC trained raters. Trained raters know exactly what they are looking for and are, in most cases, able to find more demerits than the average driver. To bridge this gap, the CRC Motor Volatility Group ran a customer perception study for cold start

and driveability in 1978 [21] at the Southwest Research Institute (SwRI) in San Antonio, Texas. The participants in this study included regular customers and trained raters. Customer demerits were compared with rater demerits to evaluate customer perception. However, the customer participants were informed of the driveability problems for the purpose of evaluation, which made them 'informed' raters. The results of the study showed that the customers ranked the fuels in the same order as the trained raters. For both sets of participants, the driveability deteriorated with decreasing fuel volatility. The average demerits for customers plotted against the average demerits for trained drivers is shown in Figure 8. Customer perception studies conducted by Clarke and Robinson [3, 22] reported similar results.

Although there was a positive correlation between customer demerits and trained rater demerits, the study did note that the trained driver scale assigned higher weightage to hesitation, stumble, and idle roughness than the customers did, while hard starting, stalls surge and backfire were under emphasized on the CRC rating scale.

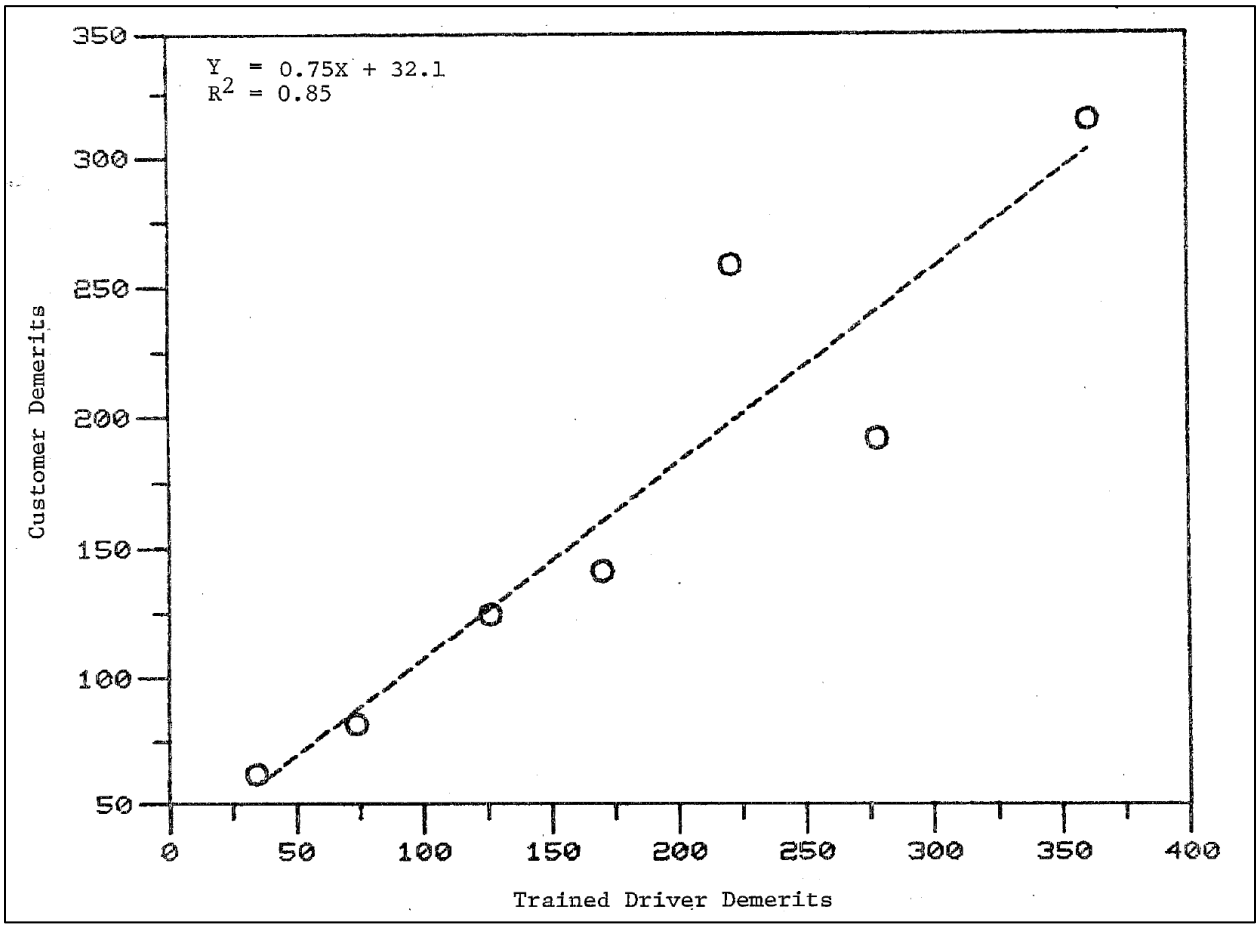


Figure 8: Customer demerits vs Trained driver demerits [21]

Driveability Models using Ambient Temperature (1979 – 1983)

Driveability studies demonstrated that in addition to fuel volatility, ambient temperature is an important variable to consider in driveability models. In CRC's study on the impact of fuel volatility on driveability at low and intermediate temperatures [23], separate predictive equations were developed for calculating demerits based on the ambient temperature for MY 1980 cars. The model for 0°F is shown in Equation 9a and for 50°F in Equation 9b.

At 0°F: TWD = 3.1 X [0.64 X (T10) + 0.31 X (T50) + 0.05 X(T90)]- 351 (9a)

At 50°F: TWD = 2.4 X [0.28 X (T10) + 0.48 X (T50) + 0.24 X(T90)]- 386 (9b)

The report quantified the relative importance of T10, T50, and T90 based on the ambient temperature, which is shown through the normalized regression coefficients in Table 2. As the ambient temperature increases, the relative importance of light end volatility (T10) decreases, while that of mid-range (T50) and back-end (T90) volatility increases. At lower temperatures, the fuel has an increased tendency to stay in the liquid state, and hence a higher fuel volatility is required to vaporize a given percentage of the fuel, irrespective of the fuel system. For this reason, the front-end volatility represented by T10 has higher importance at lower temperatures. As the temperature increases, a higher fraction of the fuel is vaporized and in equilibrium with the liquid, which reduces the importance of the front-end volatility and shifts the balance from T10 to T50 and T90. The normalized regression coefficients for the three distillation temperatures (T10, T50, and T90) for ambient temperatures ranging from -20°F to 60°F are shown in Table 2.

Table 2: Effect of ambient temperature on the relative importance of T10, T50 and T90 [23]

Normalized Regression Coefficients			
Ambient Temperature (°F)	T10	T50	T90
-20	0.73	0.27	0
0	0.64	0.31	0.05
20	0.53	0.36	0.11
40	0.39	0.43	0.18
60	0.2	0.52	0.28

The dependence of driveability models on ambient temperature was reported by other studies as well [24, 25]. Barker and Dunn [25] developed a Driveability Number (DN_T), which is a function of the logarithm of the ambient temperature, T50 and a third variable based on the shape of the gasoline distillation curve, calculated using T10, T50 and T90. The study

concluded that the driveability performance is highly dependent on (1) the ambient temperature and (2) gasoline volatility.

Driveability Task Force and the Development of the DI Equation (1979 – 1988)

Work done in the late 1960s and throughout the 1970s confirmed the dependence of driveability on fuel volatility. To get ahead of possible future changes in gasoline properties, the ASTM Subcommittee D02.A on gasoline created the Driveability Task force in 1979. The main purpose of the Driveability Task Force was to investigate the addition of Driveability Index (DI) limits (based on the equation the task force would develop) in the ASTM D439 regulation [17], which already included maximum limits on T10, T50 and T90 based on the volatility class of gasoline.

Not everyone in the ASTM D02.A Subcommittee on gasoline supported the idea of introducing a particular limiting value for the DI limit along with the distillation temperature limits in the ASTM D439 standard. Discussions with Dr. Jim Simnick [26] (previously senior fuels expert for BP, currently Simnick Consulting LLC), who was on the ASTM D02.A Subcommittee, revealed that deliberations at that time within the subcommittee got contentious. Dr. Simnick mentioned that OEMs were in support of the lower DI limits in the specification, while refiners found it problematic to make a gasoline to meet the proposed 1200°F summertime maximum for DI, while being in conformance with EPA's RVP regulations. It was especially a problem for premium fuel to be within the DI limits and RVP limits and meet the higher octane.

Dr. Scott Jorgensen [27] (previously Technical Fellow at General Motors R&D Labs, currently Hyrax Intercontinental LLC) corroborated this account by mentioning that the idea of DI being implemented into the ASTM standard was discussed and debated for about a decade with all the back and forth between the automotive and oil companies.

The Driveability Task Force solicited proprietary data from automotive and oil companies to add to the publicly available data. The data encompassed 336 vehicles which were tested using four different procedures and 92 different gasolines at temperatures between -5°F to 70°F. [5] While the data for all projects showed driveability improved with increasing volatility and ambient temperatures, it also showed a wide variability in the driveability demerits amongst the cars. To overcome this issue, the task force used the 'Median Car Model', which

[5] It should be noted that not all 336 vehicles underwent testing using the four procedures and 92 gasolines. The numbers stated are the additions from data acquired by the Driveability Task Force from all different projects used for their data analysis.

made regressions on the demerits of the median vehicle for each fuel, temperature, and fleet combination. The 'Median Car Model' is explained in detail in the landmark paper on Driveability Index (DI) by Barker, Gibbs, and Steinke [17].

The paper reports that the task force used a wide range of fuel properties including distillation temperatures and RVP as independent variables to study their impact on the driveability demerits. However, the task force was of the opinion that for an equation to be adopted into ASTM, the model would have to include T10, T50 and T90. The model also needed to be simple for blending and determination at a refinery. It should be noted that the blending of a fuel happens at various locations in the country, including the refinery, distribution terminal, and ethanol blending retail stations (ethanol and other oxygenates didn't gain prominence until the 1990s) [2, 28]. If an equation for DI contained variables such as RVP and ambient temperatures at location of intended use besides the distillation temperatures, then the oil companies would have to generate significantly more blendstocks of varying volatility besides those that are currently manufactured. To tie these discussions back to the Driveability Task Force, their decision to keep the model simple was grounded in practicality.

The initial model developed by the Driveability Task Force using 260 data points in the median car model is shown by Equation 10.

$$\textbf{DI (°C and °F)} = 1.0\times(T10) + 3.0\times(T50) + 1.0\times(T90) \quad (10)$$

Since the task force consisted of both automotive and oil industry personnel, they were well aware that many ASTM members would not find it acceptable to weigh T10 so low, which is the case in a 1-3-1 model. Another model suggested was the 1-1-0.5, which was reported as a possibility in two studies [23, 24]. However, that was not supported by the datasets analyzed by the task force. A 1-1-0.5 model put lower emphasis on T50, which previous studies had shown to have the most impact on driveability [4, 14].

The task force eliminated data sets that did not fit a good statistical design. That reduced the data to 120 points. The simplified model that came from it, shown in Equation 11, is the base hydrocarbon only model currently used for DI limits in the ASTM D4814 standard.

$$\textbf{DI} = 1.5\times T10 + 3\times T50 + 1\times T90 \quad (11)$$

Equation 11 includes the same coefficients for the distillation temperatures as Equation 1 and Equation 2, sans the ethanol factor. The Driveability Task Force did not use any oxygenated gasolines in their analysis, and explicitly stated that the equation was not meant for gasolines mixed with oxygenates (such as methyl-tertiary butyl ether (MTBE) or ethanol).

The suggestions from the study also included a proposed maximum DI limit for each volatility class of gasoline, which is shown in Table 3 below. The 'Proposed Maximum DI' was lower than the maximum DI calculated using Equation 11 (which is mentioned as 'Current DI Maximum' in Table 3) and the maximum distillation temperatures in ASTM D439, considering the purpose of the DI specification was to help prevent poor vehicle performance by eliminating the possibility of gasolines being at the maximum of two or all three of the distillation temperatures.

Table 3: Proposed driveability specifications for ASTM D439 [17]

Class	Proposed DI Maximum (°F)	Current DI Maximum (°F)	Driveability Demerits	Customer Satisfaction Percent	Percent of Commercial Gasolines Excluded	Distillation Maximum T10 (°F)	Distillation Maximum T50 (°F)	Distillation Maximum T90 (°F)
A	1310	1361	105	N/A	0.3	158	250	374
B	1290	1332	110	70	0.9	149	250 (245)	374
C	1270	1295	115	75	0.3	140	245	370 (365)
D	1235	1266	125	N/A	0.8	135 (131)	240 (235)	365
E	1200	1238	135	N/A	1.6	130 (122)	235 (230)	365

1) DI = 1.5 × T10 + 3.0 × T50 + 1.0 × T90
2) Approximate CRC TCWD at Proposed DI Levels
3) Percent Acceptance at Proposed DI Levels, 1978 CRC Customer Program
4) Current D439 Requirements, if Different, Shown in Parentheses

Adoption of the DI Equation in ASTM D4814 (1988-1998)

From the time the task force published its results, it would be 10 years before the standard was adopted by ASTM in the year 1998 (ASTM D4814-98). ASTM D439 was replaced by ASTM D4814 in 1995 (ASTM D4814-95), but the addition of the DI standards to the specification happened three years after that.

Dr. Coleman Jones (previously Technical Fellow at General Motors for fuel and biofuel implementation, currently Principal at Ambrussum Services) shed light on the situation [29]. Even though the Driveability Task Force suggested the DI equation be adopted in the ASTM standards, the oil company personnel were against the additional constraints on gasoline. The situation got dire, and the automotive companies met with the EPA around 1996 in an attempt to convince them to regulate gasoline on a federal level. EPA pointed out that D4814, the spark ignition fuel standard, was a consensus standard and declined to get involved. After that turned out to be a dead end, many automotive companies severed official ties with ASTM subcommittee D02.A. While this part of the story is not reflected in studies and driveability programs, it is important as it conveys the importance the car manufacturers put

on the regulation of gasoline and the inclusion of the Driveability Index. As Dr. Jones put it, regulating gasoline had the power to improve the performance of the existing vehicle fleet in terms of driveability, emissions, and fuel economy. Even if the automakers could engineer their way out of the fuel problem, the existing fleet would still be exposed.

To understand the EPA's perspective regarding the situation, the authors of this report did reach out to Paul Machiele, the former director of Fuel Programs Center at the EPA. Mr. Machiele mentioned that the EPA only had the authority to regulate fuel properties if it related to emissions, and could not enforce fuel standards based on driveability issues or performance alone [30]. Hence, the many emissions studies that were done at the time.

In the interim of the back and forth between the automotive companies and oil companies, the CRC conducted a customer satisfaction study in 1993 [8], in which 167 SwRI employees participated. The study established real world validation for the concept of Driveability Index. Customer satisfaction was correlated with DI calculated using Equation 11. Of all the driveability issues, 'hesitation' was the primary source of dissatisfaction, reported in 31% of the dissatisfied trips, followed by 'stall at idle' for 30% of the trips. The breakpoint between satisfaction and dissatisfaction for ethanol-gasoline blends was between DI values of 1140°F to 1250°F. For hydrocarbon only fuels (without oxygenates), the breakpoint DI range was slightly higher, between 1210°F and 1290°F. The numerical value for DI for ethanol-gasoline blends is lower as ethanol reduces the T50 of most gasolines. But the engine performance does not necessarily reflect the decrease in DI value. The first ethanol offset factor in the DI equation was included in 2006, which is discussed in a subsequent section. This range is significantly lower than the range of DI values proposed by the Driveability Task Force, shown in Table 3.

Eventually, when the first DI limits were included in the ASTM standard, the values included were lower for all grades of gasoline except class E, possibly based on data from CRC Report 585 and other studies that indicated that the DI limits needed to be lowered to account for real world driver satisfaction.

Table 4 shows the limits on the distillation temperatures and DI in ASTM D4814-98a.

Table 4: Vapor pressure and distillation class requirements (Table 1 in ASTM D4814-98a

Vapor Pressure / Distillation Class	Vapor Pressure,[A] kPa (psi)	Distillation Temperatures °C (°F), at % Evaporated. max[B]						
		10 volume %, Max	50 volume %		90 volume %, Max	End Point, Max	Distillation Residue, vol% max	Driveability Index,[C] max, °C (°F) Derived[D,E]
			Min	Max				
AA	54.7 (9.8)	70 (158)	77 (170)	121 (250)	190 (374)	225 (437)	2	597 (1250)
A	62 (9.0)	70 (158)	77 (170)	121 (250)	190 (374)	225 (437)	2	597 (1250)
B	69 (10.0)	65 (149)	77 (170)	118 (245)	190 (374)	225 (437)	2	591 (1240)
C	79 (11.5)	60 (140)	77 (170)	116 (240)	185 (365)	225 (437)	2	586 (1230)
D	93 (13.5)	55 (131)	66 (150)	113 (235)	185 (365)	225 (437)	2	580 (1220)
E	103 (15.0)	50 (122)	66(150)	110 (230)	185(365)	225 (437)	2	569 (1200)

[A] Consult EPA for approved test methods for compliance with EPA vapor pressure regulations.

[B] At 101.3 kPa pressure (760 mm Hg).

[C] Driveability Index (DI) = 1.5 × T10 + 3.0 × T50 + 1.0 × T90, where T10 = distillation temperature, °C (°F), at 10% evaporated; T50 = distillation temperature, °C (°F), at 50% evaporated; and T90 = distillation temperature, °C (°F), at 90% evaporated.

[D] The DI specification limits are applicable at the refinery or import facility as defined by 40 CFR Part 80.2 and are not subject to correction for precision of the test method.

[E] Since DI is an index and has no units, the standard temperature conversion from U.S. customary to SI units is not appropriate. Use this equation for conversion:

$$DI_{°C} = (DI_{°F} - 176.1)/1.8$$

Fuel Delivery System

An important factor that has not yet been discussed is the fuel delivery system. Though not explicitly stated in the findings, an assessment can be made that the DI equation was formulated with data mostly from carbureted vehicles. This is based on the fact that the major studies reported before the task force was established are all on carbureted vehicles, in addition to Dr. Scott Jorgensen stating it in his discussion with the authors. As the mid-1980s rolled in, the majority of gasoline spark ignition (SI) vehicles sold had PFI fuel systems, while a minority were throttle body injection (TBI) systems [31]. The 1993 customer satisfaction study [8]also looked at customer satisfaction as a function of the fuel delivery system. Table *5* shows the results from that comparison. The PFI and TBI vehicles had higher customer satisfaction for all fuels, although for the hydrocarbon and MTBE blends, the scope for improvement was minor. The most interesting result was for the ethanol-gasoline blend, which showed a markable improvement in driver satisfaction when going from carbureted to PFI or TBI fuel systems. For the fuels shown in Table *5*, the ethanol-gasoline blend contained 10% ethanol by volume, and the MTBE-gasoline blend contained 15% MTBE by volume.

Table 5: Percent customer satisfaction as a function of vehicle fuel delivery system [8]

Percent Satisfaction on Fuel				
Fuel		Carb	PFI	TBI
3	HC only	90	94	95
8	EtOH blend	64	86	85
11	MTBE blend	95	96	97

Introduction of Oxygenates to Gasoline and their Impact on Driveability (1990 – 2003)

1990 saw the enactment of the 'Oxygenated Fuels Program' [2] from the EPA, which was a program to combat urban air pollution and would require the majority of gasolines sold in the US to be blended with oxygenates such as methyl-tertiary butyl ether (MTBE) or ethanol. The requirement, according to the program, was at least 2.7% oxygen by weight (which comes out to approximately 7.8% ethanol by volume).

The CRC conducted studies to evaluate the impact of ethanol and MTBE on driveability [32-34]. CRC Report 613 [35] summarized the three phase study carried out from 1995 to 1997. The summary also included verifying the validity of new driveability models created to compare with the ASTM DI equation using data for PFI vehicles for studies ranging from 1986 to 1997.

The data was used to develop four new indices. The indices were based on:

- The original DI equation with oxygenate offsets
- An optimized T10, T50, T90 model with oxygenate offsets
- E158 and E250 with oxygenate offsets
- E70, E100, and E140 with oxygenate offsets

The equations for the four indices are shown in Table 6 below along with the R^2 values for each model's DI correlation with TWDs. NDI is 'New Driveability Index' and 'EDI' is Evaporative Driveability Index. The 'EtOH' and 'MTBE' are binary values for presence of oxygenates. 'EtOH' is 1 if ethanol is present in the fuel and '0' if it is not. The same applies for MTBE.

Table 6: R^2 values for five driveability models using data from multiple driveability studies [35]

Model	Adjusted R^2 (1995–1997)	Adjusted R^2 (1986,'89,'94)	Adjusted R^2 (1987,1988)
DI = 1.50*T10 + 3.00*T50 + 1.00*T90	0.775	0.537	0.47
NDI = 1.50*T10 + 3.00*T50 + 1.00*T90 + 86.2*EtOH + 43.2*MTBE	0.877	0.71	0.557
NDI = 1.23*T10 + 2.95*T50 + 1.00*T90 + 86.6*EtOH + 42.5*MTBE	0.877	0.712	0.554
EDI = 1.00*E158 + 2.08*E250 – 38.3*EtOH – 12.4*MTBE	0.856	0.647	0.53
EDI = 2.75*E200 + 1.00*E300 – 33.2*EtOH – 17.6*MTBE	0.757	0.696	0.557

Three of the four models that have factors for ethanol and MTBE perform better than the ASTM DI model (without the ethanol factor) for the 1995-1997 data set, while all four models perform better than the ASTM DI model for the other two data sets. This study was an early indicator that the impact of oxygenates on driveability could not be captured correctly with the initial DI equation, and an additional factor would be required for oxygenated fuels.

The study included 81 fuels in total – 9 hydrocarbon only fuels, 9 ethanol-gasoline blends and 9 MTBE-gasoline blends for each of the three phases. It would have been interesting to see how the ASTM DI equation fared with just the 27 hydrocarbon fuels without the oxygenates; whether it had a performance equivalent to the other models when oxygenates were eliminated from the equation. It would also have been interesting to compare all models using all fuels, with the DI calculated using the distillation temperatures of the base hydrocarbon before oxygenate blending.

Federal and state regulations did not mandate the use of a specific type of oxygenate. MTBE rose to the top as the oxygenate of choice for most refiners because of its availability, high octane rating, and ease of blending and distribution. By the mid 1990s, 85% of the reformulated gasoline in the entire United States contained MTBE, while only 8% of the nation's reformulated gasoline contained ethanol [28]. However, just before the turn of the millennium, issues with groundwater contamination with MTBE began to surface in California [36]. MTBE has a higher affinity for dissolving in water compared to hydrocarbons in gasoline. While the long-term health impacts of exposure to MTBE were not well known, it did cause changes to the taste and odor of water, rendering it unfit for drinking. In the year 2000, the EPA and states began regulatory control action to eliminate and phase out MTBE, and promote the production and adoption of ethanol as the primary oxygenate in gasoline. There also was significant litigation over the use of MTBE that still continues today.

Though not mentioned in any study, another drawback of MTBE is the percentage of oxygen by weight in the compound. The molecular formula for MTBE is $C_5H_{12}O$, which makes oxygen an 18.2% component by weight. The molecular formula for ethanol is C_2H_6O, in which oxygen is 34.4% by weight of the molecule. Some federal regulations required 2.7% oxygen by weight

in the fuel, which would mean a higher quantity of MTBE as compared to ethanol for the same level of oxygen in gasoline-oxygenate blend. The majority of studies on oxygenates in the 1990s used 10% by volume ethanol (approximately 3.5% oxygen by weight) and 15% by volume MTBE (approximately 2.7% Oxygen by weight), which suggests those values were required for the oxygenates to exceed the 2.7% oxygen by weight requirement. There were financial subsidies and regulatory vapor pressure relief to use 10% ethanol blends in gasoline. The reign of MTBE as the oxygenate of highest preference was short lived.

First Ethanol Offset to the DI Equation (2003 – 2006)

After the eventual demise of MTBE, work on the impact of oxygenates on driveability and the driveability index proceeded on the oxygenate that filled the vacuum, ethanol. In 2003, the CRC adopted an intermediate temperature volatility program [9] to determine the effect of ethanol on cold start and warm-up driveability. The program consisted of 10 fuels, described below. All DI calculations were done using the base DI equation shown in Equation 11, which was the one adopted in ASTM D4814-00. The report mentions that the base hydrocarbon fuel was a high DI fuel (1300°F) but does not state the reason why an out-of-specification fuel was used. The use of greater than on-specification fuels in test programs is often used to determine technical and statistical effects. The possible reason could be that it was used to promote driveability demerits, which would make it easier to differentiate between results for the base fuel and the test fuels. The DI for all fuels calculated using Equation 11 and mentioned in the report is also included below.

- Base fuel – Hydrocarbon only (DI=1296°F)
- E1 – 3% ethanol by volume splash blended with base fuel (DI=1266°F)
- E2 – 6% ethanol by volume splash blended with base fuel (DI=1263°F)
- E3 – 10% ethanol by volume splash blended with base fuel (DI=1247°F)
- E4 – 3% ethanol by volume added to hydrocarbon gasoline components to match the base fuel (DI=1295°F)
- E5 – 6% ethanol by volume added to hydrocarbon gasoline components to match the base fuel (DI=1287°F)
- E6 – 10% ethanol by volume added to hydrocarbon gasoline components to match the base fuel (DI=1301°F)
- H1 – Light hydrocarbons added to the base fuel to match the DI of E1 (DI=1267°F)
- H2 – Light hydrocarbons added to the base fuel to match the DI of E2 (DI=1271°F)
- H3 – Light hydrocarbons added to the base fuel to match the DI of E3 (DI=1247°F)

The program tested the 10 fuels on 27 vehicles (14 MY 2002 vehicles and 13 MY 2003 vehicles). All vehicles were tested by three raters, who underwent a workshop in 2002. The

workshop aimed at training new raters and calibrating experienced existing raters, which significantly improved the data quality and accuracy, as reported by the study.

- Figure 9 shows the mean corrected TWDs for all fuels. This bar chart clearly shows the effect ethanol has on driveability. When the fuels with the same DI [6] are compared, the fuel blends with ethanol have higher TWDs. The base fuel has lower TWDs than E4, E5 and E6, all of which have a DI of approximately 1300°F.
- H1, H2, and H3 have lower TWDs as compared to their corresponding ethanol blends with the same DI (E1, E2, and E3).

This is a clear indicator that the original DI equation underpredicts the driveability index of ethanol-gasoline blends. Ethanol suppresses the T50 of the fuel blend, which significantly reduces the T50. However, this reduction in T50 and the resulting DI value does not deliver improved driveability (in terms of reduced TWDs) to the same extent. The high heat of vaporization (HoV) of ethanol, resulting mixture cooling, and higher lower explosive limit (LEL) as compared to hydrocarbon-only gasoline are detrimental for cold start and warm-up driveability, and increases the effective DI of the fuel. Additional impacts of ethanol will be discussed in a section ahead. The main takeaway from Figure 9 is that the DI for ethanol-gasoline blends needs to be modified by increasing it to correctly predict the demerits.

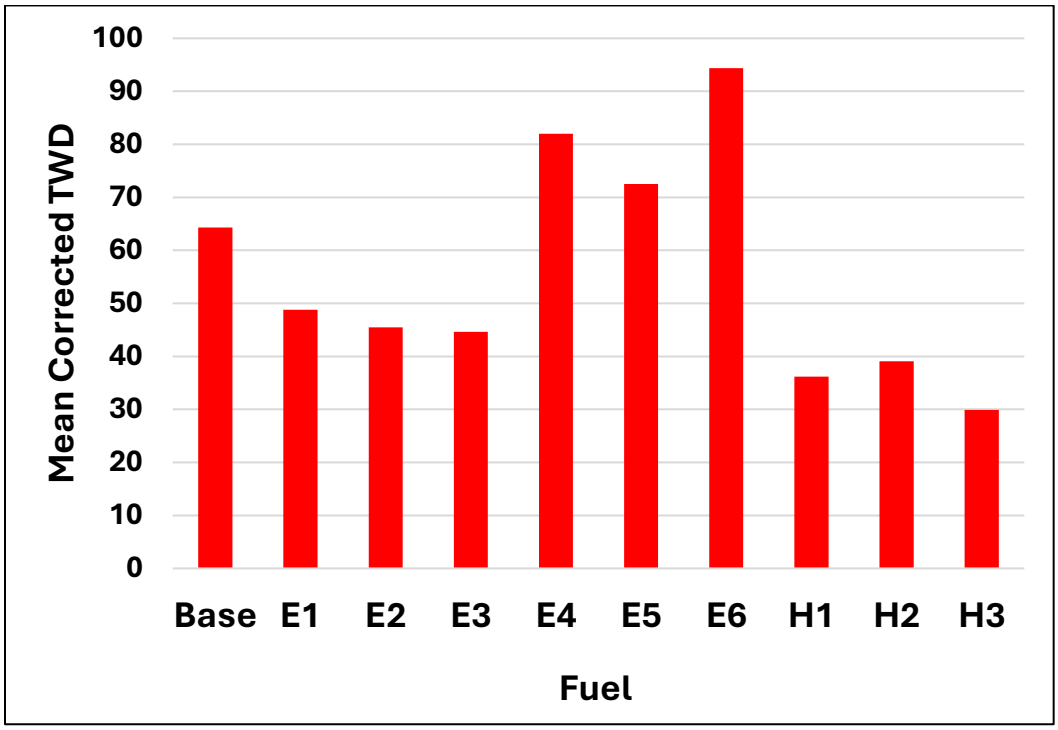


Figure 9: Mean corrected TWDs for all test fuels [9]

[6] Note that the DI values for all fuels represent ones calculated using Equation 11.

The data from the program revealed that there was a statistically significant effect of ethanol on vehicle cold start and warm-up driveability as measured by the driveability demerits. Two models were generated from the data.

- Fixed ethanol offset model
- Variable ethanol offset model

Both models exhibited a similarly high accuracy while predicting the impacts of ethanol on vehicle driveability.

Figure 10 shows the log of mean corrected TWDs with DI. All fuels containing ethanol are above the trendline, while all hydrocarbon-only fuels are below the trendline, further clarifying the picture that the effective DI of ethanol-gasoline blends is higher than their hydrocarbon only counterparts, and it needs to be reflected in the DI equation.

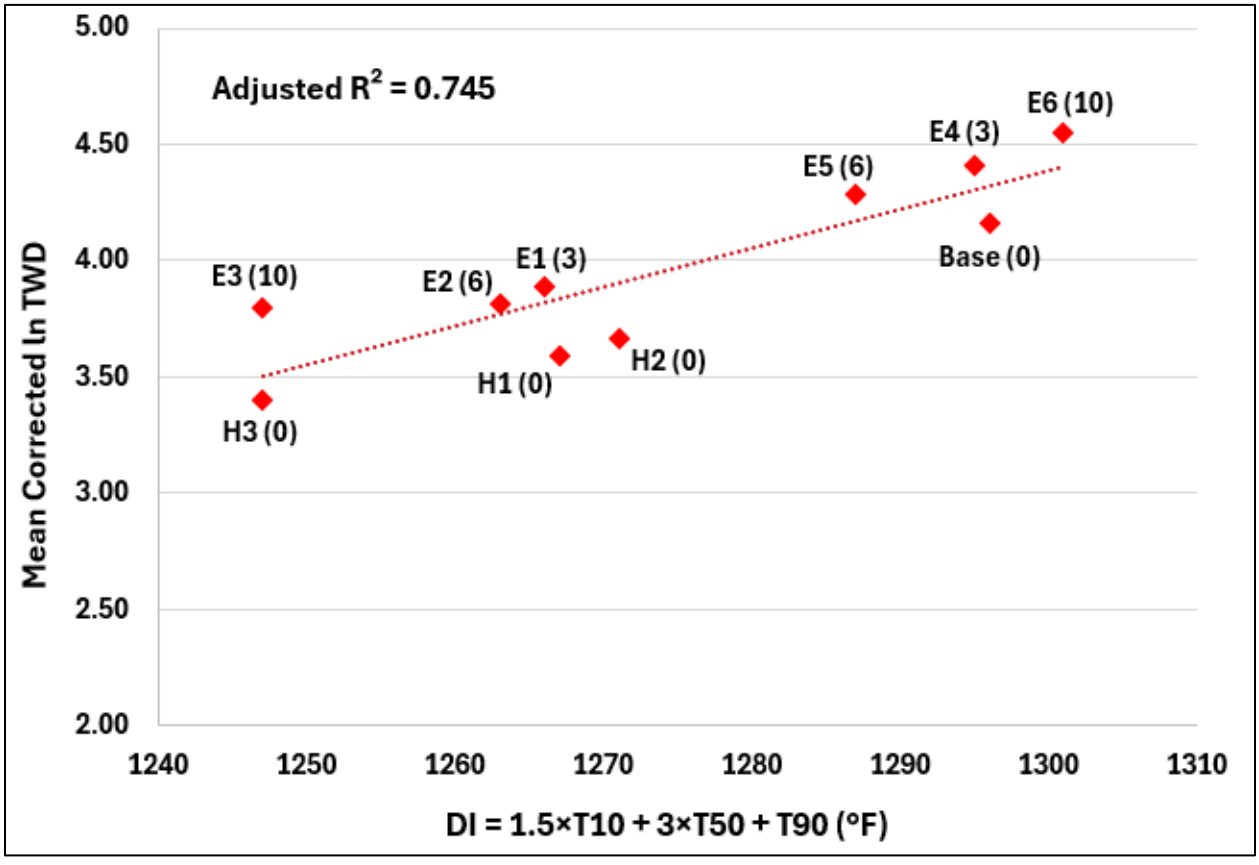


Figure 10: Mean TWDs as a function of Driveability Index (DI calculated without ethanol offset) [9]

The findings of the program were summarized by Jewitt, Gibbs and Evans [37]. Table 7, adopted from their study, shows the correlation of the driveability demerits with the base DI equation and the two models (the 'Ethanol Concentration Offset Model' and the 'Fixed Ethanol Offset Model') developed by the 2003 CRC program. The ethanol offset, either based on concentration or fixed, is much better in predicting the driveability behavior of ethanol-gasoline blends. Both models increase the DI for fuels mixed with ethanol. It should be noted that this program only used fuel blends with up to 10% ethanol, so the models apply only to fuels between E0 and E10. Note that the 'EtOH Content' multiplier in Table 7 refers to the percentage ethanol by volume.

Table 7: Driveability Index (DI) equations based on data collected for CRC Report 638 [37]

Driveability Index (DI) Equation	**Adjusted R^2**	**Root Mean Square Error (RMSE)**
DI Equation without Ethanol Offset **DI = 1.5×T10 + 3×T50 + T90**	0.745	0.191
Ethanol Concentration Offset Model **DI = 1.5×T10 + 3×T50 + T90 + 2.403×%EtOH by Volume**	0.944	0.089
Fixed Ethanol Offset Model **DI = 1.5×T10 + 3×T50 + T90 + α** **Where α=0 for hydrocarbon only fuels and α=21.01 for gasoline-ethanol blends**	0.949	0.085

In 2006, ASTM adopted the 'Ethanol Concentration Offset Model', which Equation 1 shows for the two different temperature scales.

Driveability Index (°C) = 1.5×T10 + 3.0×T50 + 1.0×T90 + 1.33×(%Ethanol by volume) (1a)

Driveability Index (°F) = 1.5×T10 + 3.0×T50 + 1.0×T90 + 2.4×(%Ethanol by volume) (1b)

The update to the ASTM D4814-06a table with the DI specifications is shown in Table 8. Note that the change was reflected only in the footnotes (footnote D).

Table 8: Vapor pressure and distillation class requirements (Table 1 from ASTM D4814-06a)

Vapor Pressure / Distillation Class	Vapor Pressure,[B] kPa (psi)	Distillation Temperatures °C (°F), at % Evaporated. max[C]					Distillation Residue, vol% max	Driveability Index,[D] max, °C (°F) Derived[E,F]
		10 volume % , Max	50 volume %		90 volume %, Max	End Point, Max		
			Min	Max				
AA	54 (7.8)	70 (158)	77 (170)	121 (250)	190 (374)	225 (437)	2	597 (1250)
A	62 (9.0)	70 (158)	77 (170)	121 (250)	190 (374)	225 (437)	2	597 (1250)
B	69 (10.0)	65 (149)	77 (170)	118 (245)	190 (374)	225 (437)	2	591 (1240)
C	79 (11.5)	60 (140)	77 (170)	116 (240)	185 (365)	225 (437)	2	586 (1230)
D	93 (13.5)	55 (131)	66 (150)	113 (235)	185 (365)	225 (437)	2	580 (1220)
E	103 (15.0)	50 (122)	66(150)	110 (230)	185(365)	225 (437)	2	569 (1200)

[A] See 1.7 for determining conformance with specification limits in this table.
[B] Consult EPA for approved test methods for compliance with EPA vapor pressure regulations.
[C] At 101.3 kPa pressure (760 mm Hg).
[D] Driveability Index (DI) = 1.5×T10 + 3.0×T50 + 1.0×T90 + 1.33°C (2.4)×E (E = Ethanol Volume %) where
T_10 = distillation temperature, °C (°F), at 10% evaporated;
T_50 = distillation temperature, °C (°F), at 50% evaporated;
T_90 = distillation temperature, °C (°F), at 90% evaporated, and 1.33 is the coefficient for the volume % ethanol present when the distillation results are determined in degrees Celsius and 2.4 is the coefficient when distillation results are determined in degrees Fahrenheit.
[E] The DI specification limits are applicable at the refinery or import facilities defined by 40 CFR Part 80.2 and are not subject to correction for precision of the test method.
[F] Since DI is an index and has no units, the standard temperature conversion from U.S. customary to SI units is not appropriate. The following equation is to be used to make the conversion: $DI_{°C} = (DI_{°F} - 176)/1.8$

Impact of the T70 Bump on Driveability (2005 – 2008)

In the period between 2005 and 2007, automotive companies experienced an increase in the number of driveability related complaints. This issue was highlighted by General Motors' fuel expert, Dr. Pat Geng, in the discussion the authors had with him [38]. Dr. Geng mentioned that the driveability issues were caused by fuels that, while adhering to the ASTM D4814 requirements, had a high T70. General Motors conducted an internal study [39] to evaluate the impact of high T70 fuels while communicating with the CRC and ASTM. The properties of the fuels tested in the study are shown in Table 9. The study confirmed that for fuels with similar DI, a fuel with higher T70 resulted in more driveability issues. The study also reiterated the importance of the DI limits in the ASTM D4814 specification.

Table 9: Fuel properties for study evaluating the impact of high T30 and high T70 on driveability [39]

Test Method	Property	HIDI T30,T70	HIDI T70	HIDI	Tier 2	RVP9	RVP7
ASTM D 5191	DVPE psi	6.6	6.65	6.7	9.1	9	7.2
ASTM D 4052	SG	0.75	0.748		0.742	0.719	
ASTM D 2699/2700	Antiknock Index	91.5	92.1	92.3	92.3	88	
ASTM D 1319	Aromatics vol%	29.4	29.6	29.6	29.4	18.2	
	Olefins vol%	0.6	0.4	1.1	0.6	3.6	
	Saturates vol%	70	70	69.3	70	78.2	
ASTM D 5291	Carbon wt%	86.38	86.31		86.37	85.5	
	Hydrogen wt%	13.62	13.69		13.43	14.5	
	Nitrogen wt%	<0.5	<0.5		<0.5		
	Oxygen wt%	<0.5	<0.5		<0.5		
ASTM D 86	DI (°F)	1294	1255	1255	1175	1135	1179
ASTM D 381	Unwashed gum	27.5	30	4		1.2	
	Washed gum	<0.5	<0.5	1	<0.5	0.4	
ASTM D 86	IBP °C	38.6	36.8	36.5	31.7	31.1	37.6
ASTM D 86	T10 °C	64.8	59.5	66.1	52	50.6	59.3
	T30 °C	99.2	85.5	93.4	76.9	75	78.5
	T50 °C	116.8	112.3	111.1	106.6	101.7	101.2
	T70 °C	149.7	151.4	127.8	120.5	114.4	122.3
	T90 °C	173.5	173.5	181.1	160	151.1	165.7
	FBP °C	213.3	215.1	205.4	206.9	206.1	216.7

Dr. Geng brought up this issue to Dr. Jim Simnick (working with BP at the time) and Jeff Jetter (working with Honda at the time), the co-chairs of the CRC Performance Committee. The discussion amongst the committee members went in the direction of not adding T70 to the DI equation specification, as it would require an unreasonable amount of time and data to verify the findings. A compromise was reached to include verbiage in the specification that suggested the oil companies follow a certain rule while blending gasoline, where the T70 value was not more than 12°C (22°F) higher as compared to the average of T50 and T90. This is shown in Equation 12.

T70 Bump difference: T70 – (T50+T90)/2 < 12°C (22°F) (12)

This was introduced to the specification in 2008 ASTM D4814-08 version. The exact wording is as follows:

The extent of a fuel's deviation from a normal distillation slope can be quantified by determining the difference between the measured 70 % evaporated temperatures and a calculated value, which is approximated by the arithmetic average of the 50 % and 90 % evaporated temperatures. Vehicle testing has shown if the difference between the measure and calculated 70 % evaporated temperature is less than 12°C (22°F), average vehicle driveability, as measured by trained raters is comparable to fuel with a standard distillation curve. When the difference is greater than 12°C (22°F), average vehicle driveability is degraded. The difference is determined using the following equation:

$$T70\ Bump\ difference = T70 - (T50+T90)/2$$

Dr. Jim Simnick provided a detailed version of this account as well [26].

"Broadly, a refiner can make a gasoline that's going to meet all of the ASTM D4814, including driveability, but it can run very poorly in a vehicle, and that was observed when some refiners were making a gasoline that had a hump in it. If you looked at the distillation curve, there was a vertical ascending bump right around T70 indicating a large number of heavier hydrocarbons. That gasoline could run poorly in terms of cold start and warm-up but yet would still meet the Driveability Index (DI). Not many gasolines had this issue, but we did find a few. And that issue was brought up at ASTM, and there was some OEM initiative effort to try to quantify that. We worked on that particular issue and found that we could put some information into the D4814 specification about this issue because it was greatly restricted to one or two refiners, and it was an occasional incident. So, the compromise was to put this in there and advise refiners to watch out for this property. If they need to institute an internal specification to their company, they could do that to ensure they made a good performing gasoline."

Dr. Simnick speculated that the T70 bump was caused due to heavy aromatic compounds that were hard to vaporize, which caused poor air-fuel ratio control under cold start and warm-up conditions.

Second Ethanol Offset to the DI Equation (2011 – 2016)

In January 2011, the EPA granted the final version of a partial waiver to allow the sale of gasoline-ethanol blends that contain greater than 10% ethanol by volume (E10) and up to 15% ethanol by volume (E15) for use in light duty vehicles. Going from E10 to E15 further lowers the mid-section of the distillation curve and increases the heat of vaporization of the mixture. CRC adopted a program in 2013 [10] to determine the ethanol offset in the DI equation for ethanol blends from 10% to 20% by volume as a response to a request from ASTM. Although the program studied fuels up to E20, the specification would include an offset only up to E15, since the EPA waiver was only for fuel with greater than 10% but up to

15% ethanol by volume. Testing up to 20% ethanol by volume was simply to analyze the impact of ethanol in ethanol-gasoline blends beyond E15.

The program tested 10 fuels on MY 2012 vehicles. The vehicles were predominantly PFI (14 out of 18). Four vehicles with direct injection spark ignition (DISI) or GDI were used as well. The base fuel was a hydrocarbon only fuel with a DI of 1250°F. The distribution of fuels based on ethanol content is shown below. The uncorrected DI values calculated using Equation 11 without any ethanol correction are included below.

- E0 – 4 fuels (DI values of 1251°F, 1164°F, 1042°F, 999°F)
- E10 - 2 fuels (DI values of 1161°F, 1045°F)
- E15 – 2 fuels (DI values of 1051°F, 1063°F)
- E20 - 2 fuels (1055°F, 1046°F)

Table 10 shows the fit comparisons (R^2 values) for the natural log of total weighted demerits plotted against two ethanol offsets. The 2.4 ethanol offset value comes from the work done to include the first ethanol correction factor in ASTM D4814 [9, 37]. The 9.49 ethanol offset value was derived from the regression analysis conducted for CRC Report 666. The regression analysis included E0, E10, E15, and E20 fuels and showed that ethanol at higher concentrations has a much stronger effect on driveability (R^2=0.886) than the 2.4 factor (R^2=0.483). The 9.49 ethanol coefficient also showed high statistical significance (p=0.0004), indicating that the effect of ethanol on the DI equation is real and substantial.

Table 10: Fit comparison of ethanol offsets for various fuel combinations [10]

Fuel Combinations	Ethanol Offset	R^2 for Linear Fit
E0	NA	0.919
E0, E10	2.4	0.906
E0, E10	9.49	0.875
E0, E15	2.4	0.557
E0, E15	9.49	0.933
E0, E20	2.4	0.538
E0, E20	9.49	0.94
E0, E10, E15	2.4	0.613
E0, E10, E15	9.49	0.871
All fuels	2.4	0.483
All fuels	9.49	0.886

For fuels up to 10% ethanol, the R^2 values are high for the equation introduced in ASTM D4814-06, with the 2.4 offset for ethanol (for the DI value in °F). The R^2 values plummet to

below 0.65 in all cases where E15 and E20 fuels are included in the regression analysis but are high with the ethanol offset increased to 9.49. The results indicate that a change was required in the specification for fuels that contained more than 10% but no greater than 15% ethanol. Conclusions of the CRC program suggested ASTM adopt a constant offset for fuels ranging from E10 to E15.

The recommendation was eventually accepted by ASTM in 2016, albeit with a slight modification. ASTM D4814-16b was the first update to include the equation for ethanol gasoline blends from 10% to up to 15% ethanol by volume. But since CRC-666 did not test any fuels between E10 and E15, the exact ethanol percentage where the first ethanol offset DI equation (Equation 1) stops being valid, could not be identified. ASTM therefore introduced a linear interpolation between the 2.4 coefficient (valid through E10) and the 9.49 coefficient found at E15. The final model, which is still in use in the year 2025, is the one shown in Equation 2.

The exact wording in the ASTM D4814-25 specification regarding the modification to the equation is stated below.

There are insufficient data for fuels with ethanol concentrations between 10% and 15% by volume to establish the type of change in this range. The consensus approach is to proportionally change the ethanol coefficient from the current 1.33 °C (2.4 °F) at 10 % by volume ethanol to 5.26 °C (9.49 °F) at 15 % by volume. API report "Determination of the Potential Property Ranges of Mid-Level Ethanol Blends"14 provides data to support a linear relationship. This proportional approach will be reconsidered when additional data become available.

Driveability Index (°C) = 1.5×T10 + 3.0×T50 + 1.0×T90 + (1.33 + [(%Ethanol by volume-10)/5)]×(5.26-1.33))×(%Ethanol by volume) (2a)

Driveability Index (°F) = 1.5×T10 + 3.0×T50 + 1.0×T90 + (2.4 + [(%Ethanol by volume-10)/5)]×(9.49-2.4))×(%Ethanol by volume) (2b)

Change in Footnote I Regarding the Application of the DI Specification Limits (2021)

Since the adoption of Equation 2 into ASTM D4814, the only change the specification has undergone with regards to DI is change in footnote I. This change was introduced in version ASTM D4814-21c. The differences in the footnote before the most recent change are shown below.

ASTM D4814-21b – The DI specification limits are applicable **at the refinery or import facility as defined by 40 CFR Part 80.2** and are not subject to correction for precision of the test method.

ASTM D4814-21 c – The DI specification limits are applicable **at the fuel manufacturing facility** and are not subject to correction for precision of the test method.

The updated wording decoupled ASTM's DI requirement from EPA definitions and clarified that DI must be met at the point where the finished gasoline is actually manufactured, including terminals where ethanol blending occurs.

A timeline of events impacting Driveability Index and the ASTM D4814 standard are shown in Figure 11.

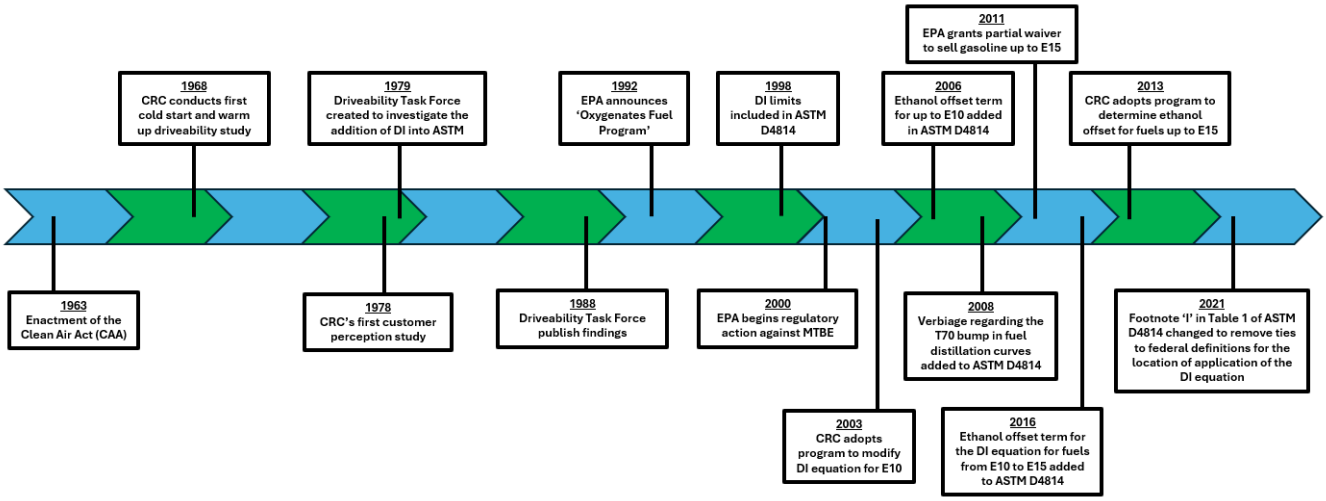
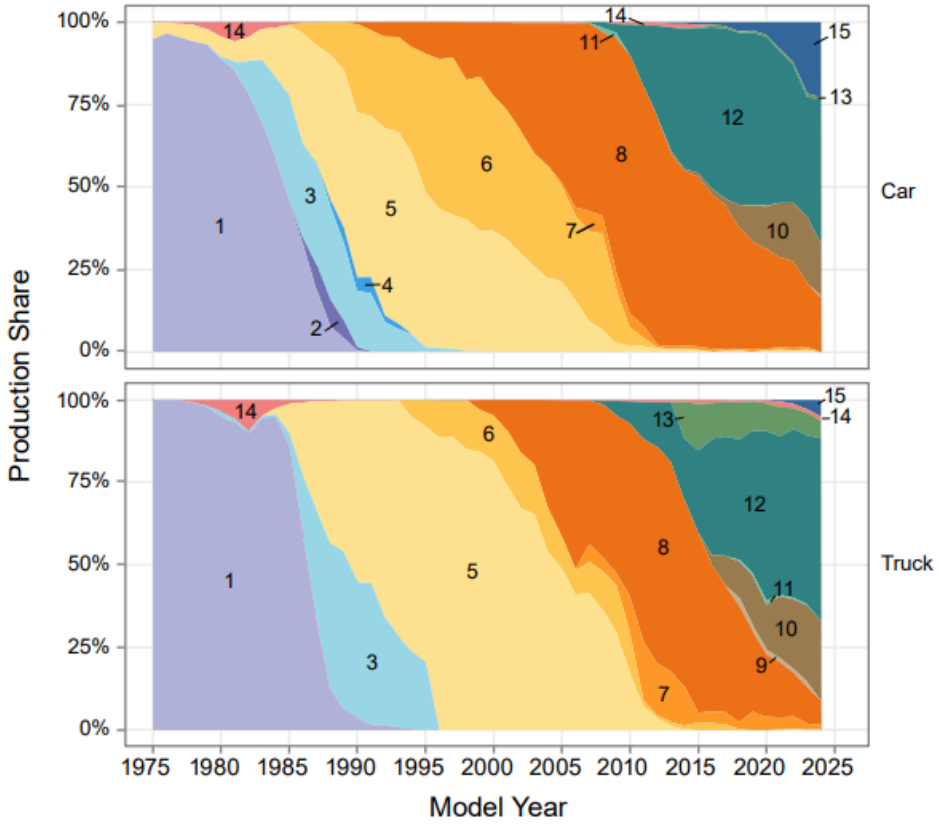


Figure 11: Timeline of events impacting Driveability Index and the ASTM D4814 standard

This section provided a detailed history of the Driveability Index, from the reasons behind its conception, the work done developing the optimum model, to its actual integration into ASTM D4814 and all the changes that have been made to it since. The next section discusses the upgrades in technology that have altered the relationship between SI engines and gasoline volatility.

Engine and Vehicle Technology

When the first investigations by the CRC into driveability and its linkage to fuel volatility were initiated in the late 1960s, the automotive technology landscape in the United States was vastly different than it is today. As late as the mid-1980s, over 90% of US light-duty vehicles had relatively large displacement, carbureted, two-valve per cylinder engines with fixed cam timing, as shown in Figure 12.



Fuel Delivery	Valve Timing	Number of Valves	Key
Carbureted	Fixed	Two-Valve	1
		Multi-Valve	2
Throttle Body Injection	Fixed	Two-Valve	3
		Multi-Valve	4
Port Fuel Injection	Fixed	Two-Valve	5
		Multi-Valve	6
	Variable	Two-Valve	7
		Multi-Valve	8
Gasoline Direct Injection (GDPI)	Fixed	Multi-Valve	9
	Variable	Multi-Valve	10
Gasoline Direct Injection (GDI)	Fixed	Multi-Valve	11
	Variable	Multi-Valve	12
		Two-Valve	13
Diesel	–	–	14
BEV/FCEV	–	–	15

Figure 12: Engine architecture market share in the United States over time [40]

In the ensuing decades there have been dramatic changes in vehicle and engine technology, primarily focused on improvements in emissions, fuel economy, and performance to meet ever more stringent standards. Some of the key areas impacting driveability and sensitivity to fuel volatility characteristics include:

- Engine:
    - Engine fueling systems moving from carburetion, to throttle body injection (TBI) to port fuel injection (PFI) to progressively higher-pressure gasoline direct injection (GDI)
    - Introduction of overhead cam (OHC) valvetrains with four valves per cylinder
    - Variable camshaft timing and valve lift
    - Cylinder deactivation
    - Start-stop systems
    - Higher secondary spark energy, multiple strike strategies, timing control, and spark plug technology
    - Boosting and downsizing
- Vehicle:
    - Downspeeding with increased gear count transmissions
    - Hybridization
    - On-board vapor recovery systems
    - Catalytic converters
    - Electronic, closed-loop engine controls
    - Increased electrical loads (daytime running lights, heated seats, etc.)
    - Increased parasitic loads (air conditioning, power steering, etc.)

The other area of major change has been emissions regulations. When the impact of fuel volatility was first investigated, emission regulations were in the early stages of adoption with very lenient limits on constituent emissions (HC, NOx, CO) by today's standards. This allowed fuel enrichment levels, especially during cold starts and warm-up operation, to be calibrated at relatively rich levels providing robustness against variation in fuel volatility.

One of the main factors influencing cold engine start-up and warm-up driveability issues is the ability to generate a sufficiently rich air/fuel mixture in the engine cylinder at the time of ignition and combustion. If the mixture is too lean (excess air) the ignition and flame propagation processes will become slower and less robust resulting in late burning cycles that produce less work output (i.e. lower indicated mean effective pressure - IMEP) or, in the extreme, partial burns or misfires. These combustion phenomena can manifest themselves as idle roughness, hesitation, stumble, or surge as experienced by the driver.

The air/fuel ratio, in turn, is governed by the amount of fuel injected and the proportion of that fuel that is evaporated between the time the fuel is injected and the ignition event. Factors influencing this proportion include the volatility characteristics of the fuel (i.e. the shape of the distillation curve), heat of vaporization of the fuel, the droplet size distribution of the injected fuel, the residence time prior to ignition, and the temperature and pressure of the air at the time the fuel is injected into or the wall temperature the injected fuel contacts.

The fundamental influence of each of these is described below:

- Fuel Volatility Characteristics
    - Fuels with lower distillation temperatures will evaporate more completely at a given temperature and pressure.
- Fuel Heat of Vaporization
    - As fuel evaporates it removes energy from the surrounding material (air, remaining liquid fuel, wall surfaces) lowering the effective temperature and hindering further evaporation.
    - This effect is greater for fuels with higher heat of vaporization such as ethanol.
        - For reference, ethanol has a heat of vaporization of around 850 kJ/kg while standard gasoline hydrocarbon components are in the range of 350 to 400 kJ/kg.
- Droplet Size Distribution
    - Vaporization occurs on the exterior surface of fuel droplets or puddles.
    - Smaller droplets result in higher surface to volume ratio exposing more fuel surface area and increasing the rate of vaporization.
- Residence Time
    - The longer a fuel droplet or puddle is exposed, the higher the percentage of that fuel that will evaporate.
- Air Temperature (and wall temperature for fuel puddles)
    - The higher the temperature of the air that the fuel droplet is in contact with, the higher the percentage of the fuel at the surface of the droplet or puddle that will be above its distillation temperature.
- Air Pressure
    - Higher pressure surrounding the fuel droplet will suppress the evaporation process.
    - Higher pressure effectively shifts the distillation curve to higher temperatures similar to impact of altitude on the boiling point of water.

Many of the changes in technology influence one or more of these factors and hence impact the fuel vaporization process. Some have provided increased robustness and decreased

sensitivity to fuel characteristics such as volatility, DI and heat of vaporization while others have at least partially negated those benefits. In all cases, the potential benefits provided by the technology enhancements have been at least partially offset by calibration and control changes to meet stricter emissions standards as detailed later in this report.

Fueling Systems

Since the 1960s the predominant fuel system for light duty gasoline vehicles in the United States has shifted from carburetors to a mix of direct injection and port injection as shown in Figure 13.

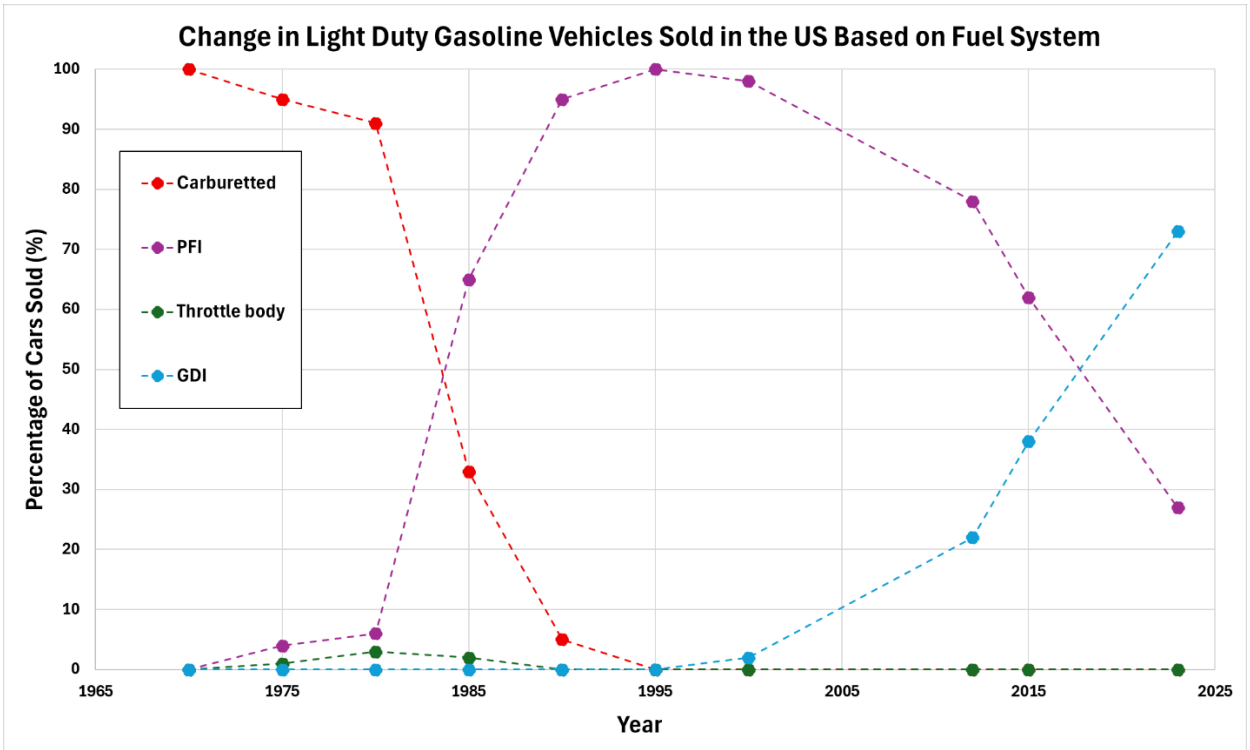


Figure 13: Fuel system market share in the United States over time [31, 40, 41]

The shift in fueling technology impacts the fuel vaporization in several key areas:

- Droplet size
- Residence time
- Local air and wall temperature warm-up rates

Carburetors utilized fuel pressure typically in the range of 4 to 6 psi gauge (30 to 40 kPa) and produced relatively large fuel droplets, especially at lower engine speeds and loads. The droplet size was inversely proportional to the airflow rate through the venturi, so at cranking

speeds and light engine loads the droplets would tend to be at the larger end of the range. Due to their location at the entrance to the intake manifold, carburetors did provide longer residence time for fuel to evaporate. But that location also meant that the surrounding material was farther from the engine coolant and exhaust and took longer to warm-up after a cold start. During this time, there could be substantial puddling of the unevaporated, higher boiling point fuel components. Coupled with the long distance between the fuel injection point and the cylinder, this led to poor transient air/fuel ratio control. During tip-in maneuvers, the engine could experience lean excursions leading to stumbles or hesitation. This could be partially compensated through the use of accelerator pumps to add additional fuel when the throttle was opened. But these fixed, open loop systems could not compensate for variations in fuel distillation characteristics or ethanol concentration.

The adoption of port fuel injection (PFI) provided notable improvements in many of these key areas. They operated at a fuel pressure about an order of magnitude higher than carburetors (300 to 400 kPa). Average fuel droplet size of around 120 to 200 μm [42] is typically slightly smaller than for carburetors which is directionally correct for improved vaporization. As with carburetors, PFI systems typically have fuel impingement on the surrounding surfaces – in this case the intake port walls and back side of the intake valves. Due to the proximity to the combustion system and coolant passages, the surrounding material temperatures increase faster and to higher levels during warm-up than for carburetors aiding evaporation. More significant for warm-up driveability is that the fuel is injected much closer to the cylinder – typically in the intake port – providing improved transient air/fuel ratio control. An added benefit of the higher fuel system pressure is the suppression of vaporization within the fuel lines which decreased sensitivity to hot fuel handling issues such as vapor lock. Scott Jorgensen, formerly with General Motors, noted that in the early driveability evaluations comparing PFI and carbureted vehicles “PFI cars were better, but they were by no means immune [27].”

As shown in Figure 13, since about 2005 PFI has been gradually replaced in the light duty market by gasoline direct injection (GDI) with greater than 70% market share in 2025. These systems move the injector into the combustion chamber and add a high-pressure boost pump to the fuel system. Supply pressure to the high-pressure pump is similar to a PFI system (300 to 400 kPa) but the fuel pressure at the injectors is one to two orders of magnitude higher. Early systems operated in the range of 50 to 100 bar (5,000 to 10,000 kPa). Modern systems are moving to pressures in the 300 to 500 bar range in an effort to control particulate matter emissions. Due to the much higher injection pressure, the injected fuel droplet size is roughly an order of magnitude smaller than for PFI applications, typically less than 20 μm [42]. This results in markedly higher surface to volume ratio and faster vaporization. The time it takes a droplet to fully evaporate at a given temperature and

pressure condition is proportional to the square of its diameter as governed by the *D^2 law* for droplet evaporation, which is shown in Equation 13 [43].

$$t_d = D_0^2/K \quad (13)$$

Where: t_d is the time it takes a droplet to fully evaporate (droplet lifetime)
D_0 is the initial droplet diameter
K is the evaporation constant

This effect, though, is at least partially offset by reduced residence time for vaporization to occur and for mixing of the fuel vapor and air. In PFI applications the fuel is normally injected when the intake valve is closed (during the compression stroke of the previous cycle) while in a typical GDI application it is injected during the intake stroke. Depending on the specific injection timings and the load (injection duration), fuel in a PFI application has 2 to 3 times as long to vaporize prior to the compression event. Since the fuel is injected directly into the cylinder for GDI, the surrounding temperatures start to increase immediately following the first combustion which should, in theory, further decrease sensitivity to fuel volatility during warm-up.

Figure 14, taken from CRC Report No. 666 [10], compares total weighted demerits for 2012 and 2013 MY vehicles with GDI (labeled DISI in Figure 14) and PFI fuel systems. While not a direct, controlled A-B comparison as these were in different vehicles from different OEMs, the data suggests that implementation of GDI alone was not sufficient to eliminate driveability issues. Several factors may have contributed to the higher TWDs for the GDI vehicles:

- Model years 2012 and 2013 were at the very start of GDI introduction into the mainstream light duty vehicle market. The injection hardware and calibrations were relatively immature compared to legacy PFI systems and new approaches, such as aggressive catalyst light-off strategies with split injection schemes, were being introduced.
- It should also be noted that GDI injection pressures have risen significantly since 2013 so the data shown here may not be representative of more modern GDI vehicles.

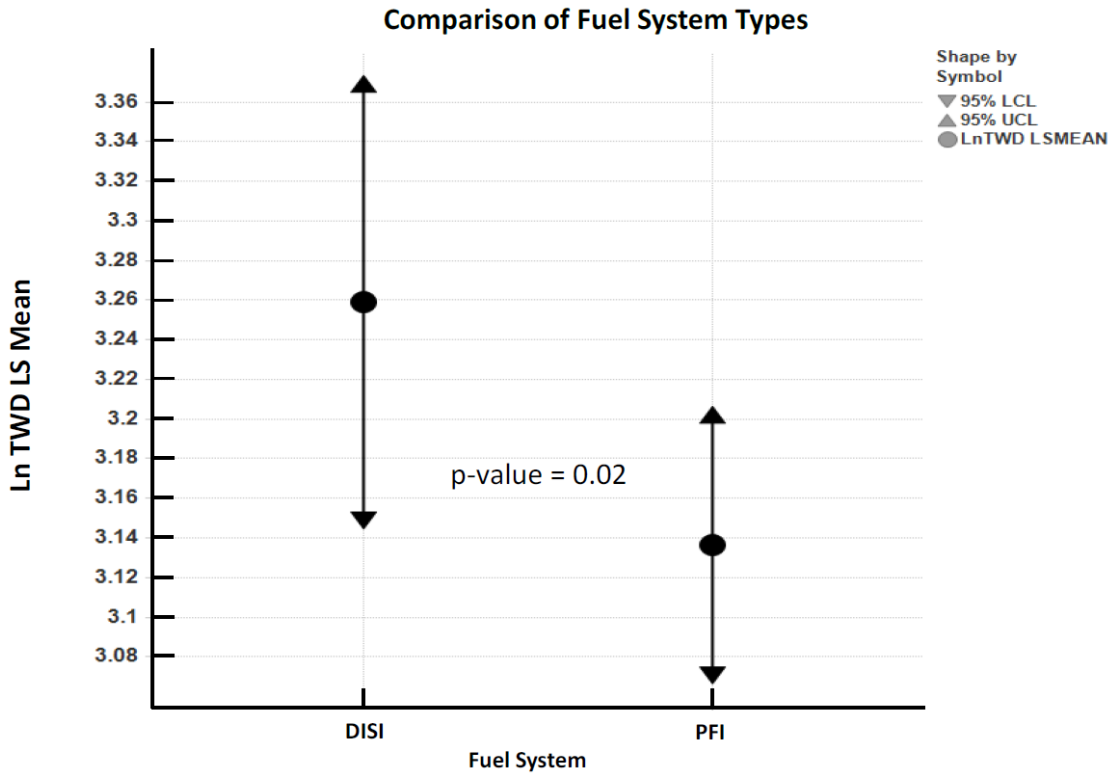


Figure 14: Total weighted demerits for GDI (DISI) and PFI vehicles [10]

Valvetrain Technologies

Up until the mid-1990's most light-duty vehicles in the United States utilized two valves per cylinder and fixed timing of the camshaft(s) relative to the crank (see Figure 12). As shown in Figure 12 the scenario has shifted markedly since then with a majority of light-duty vehicles utilizing four valves per cylinder and some form of variable valve actuation. The types of variable valvetrain control include:

- Variable camshaft phasing (relative to the crank)
- Variable valve lift
- Cylinder deactivation

Depending on the specific implementation, the primary purpose of variable valve actuation systems is to improve engine efficiency by reducing pumping losses through either reduction of volumetric efficiency or an increase in the internal dilution levels in the engine. The result, at part load conditions, is an increase in the manifold absolute pressure at a given load.

A secondary effect of many variable valvetrain systems is an increase in specific power and torque of the engine. This allows for a moderate reduction on engine displacement for the

same vehicle performance level and a further increase in intake manifold pressure at a given load.

Variable valvetrain systems can also impact startability and emissions in the first several seconds after engine startup, but before oil pressure is sufficient to phase the cams. The major influence here is if the intake camshaft is parked in an advanced or retarded position. Parking the intake cam retarded decreases effective compression ratio and decreases valve overlap. The reduced effective compression ratio can reduce ignitability of the mixture, especially on the first fire able cycle. Reduced overlap reduces exhaust rebreathing which can lead to increased engine out HC emissions and decreased fuel vaporization from the hot rebreathed exhaust.

Downsize Boosting / Displacement

Another significant trend in vehicle technology in the last several decades has been the introduction of boosting and downsizing, accounting for around 45% of the market in MY 2024 as shown in Figure 15. While early applications of turbocharging (or supercharging) were focused on increased vehicle performance, modern applications are targeted at increased efficiency and lower CO_2 emissions. The addition of the boosting device enables markedly higher specific torque and power from an engine. This in turn allows for a significant reduction in engine displacement to achieve the same level of vehicle performance.

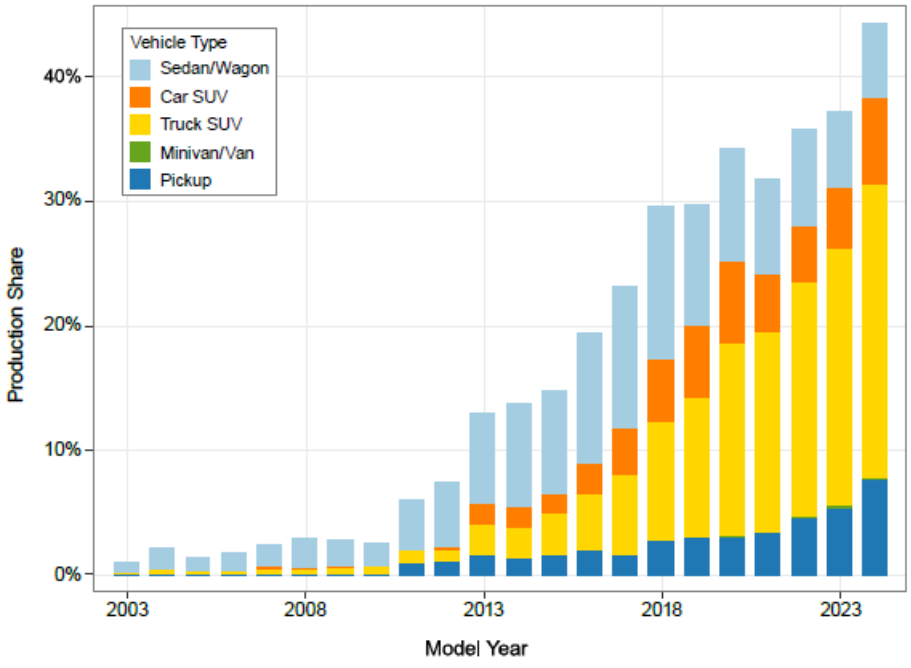


Figure 15: US market penetration of turbocharging for MY 2024 [40]

Other technological advances including multi-valve cylinder heads, fuel injection, cam phasing, and electronic engine controls have also contributed to engine downsizing at similar performance levels. Since 1975 the average displacement has dropped from just under 5.0L to about 2.8L in 2023. When the engine displacement is reduced, producing a given power level requires a higher specific output (i.e. Nm/L) which, in turn, requires a denser cylinder charge and higher intake manifold pressure. This reduces pumping losses leading to improved efficiency. This also means that tip-in maneuvers are at a much higher manifold pressure as well, which affects fuel vaporization.

Downspeeding

Pumping losses can also be reduced by operating the engine at a lower speed. Maintaining a specific vehicle speed or rate of acceleration requires a specific power output from the engine. Since power is a function of engine torque and engine speed, reducing the engine speed requires higher torque to generate the same power. Further, higher torque requires higher intake manifold pressure. The impact of downspeeding on fuel vaporization can be complex. Higher intake manifold pressure can decrease vaporization; however, lower engine speeds provide additional time for vaporization.

Downspeeding is accomplished through the introduction of higher gear count transmissions and the use of electronically controlled torque converter clutches.

Hybridization

Hybridization has also made significant inroads in market penetration in recent years. Hybrid vehicles span a broad range of complexity including:

- Start-stop systems where the engine is turned off at idle under certain conditions
- “Mild” hybrids (MHEVs) – offer some propulsion assistance and can recuperate some braking energy but can’t directly power the vehicle
- Standard hybrids (HEVs) – can drive in electric only mode under certain conditions (generally higher voltage and larger battery capacity than MHEV)
- Plug in hybrids (PHEV) - can drive under electric only mode under certain conditions and can be charged from an external power source

Mild and standard hybrids, as shown in Figure 16, accounted for about 15% of the market in MY 2024. PHEVs accounted for roughly another 3% market share [40].

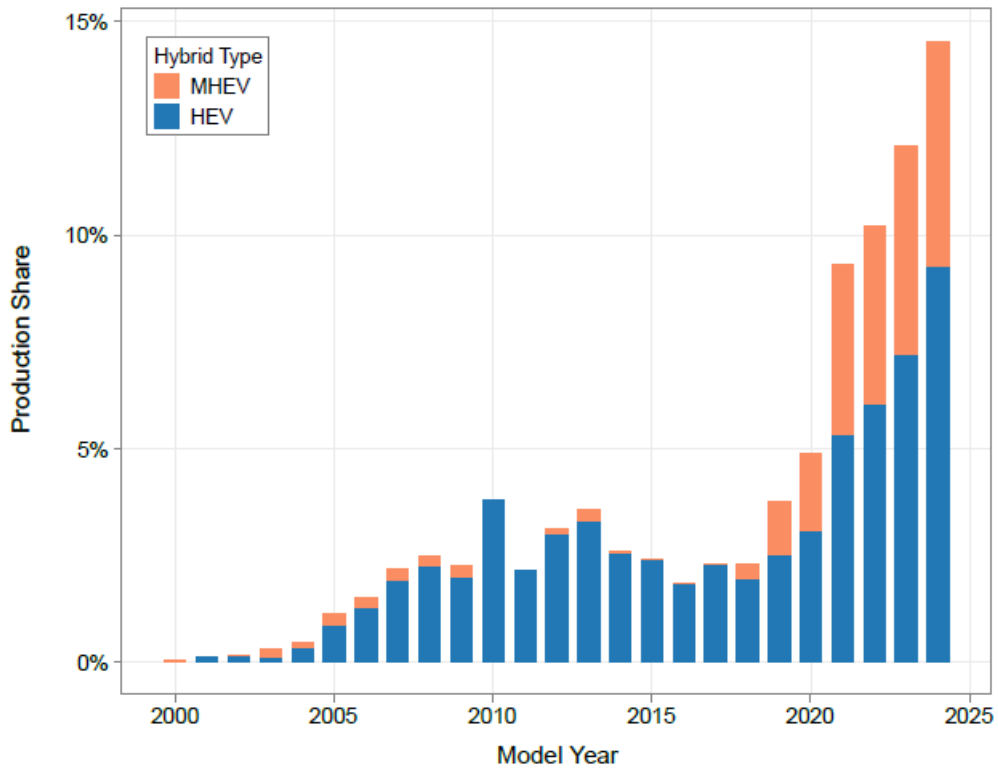


Figure 16: US market penetration of hybrid vehicles (exclusive of PHEV) [40]

In all cases, though, the impact of hybridization on the engine is to regenerate braking energy and reduce the engine operating time and increase the average load on the engine when it is operational. This change in the operating duty cycle of the engine can impact sensitivity to fuel volatility in several ways:

- Higher engine loads lead to increased manifold pressure
- In some applications the engine is required to generate relatively high loads immediately after starting without the typical "warm up" transition
- Long "engine off" periods can increase the amount of operation in the "cold" and "warm up" phases that are more sensitive to fuel volatility

In the case of HEVs and PHEVs there may be opportunities to utilize the electric motor and controls architecture to mitigate some of the driveability issues associated with high DI fuels. For example, it may be possible to start the engine at higher engine speeds and vacuum levels. The electric motor may then be able to assist in torque delivery as the engine warms up enough to tolerate the higher loads.

Electrical and Parasitic Loads

Over the last several decades there has also been a notable increase in parasitic engine loads in light duty vehicles. Daytime running lights, heated seats and steering wheels, elaborate infotainment and advanced driver assistance systems (ADAS), higher market penetration of power steering, etc. all act to increase the engine load either directly or through higher electrical loads on the alternator. Heated seats and steering wheels, in particular, add loads at colder ambient temperatures where driveability issues are more prevalent.

Effect of Manifold Pressure

As noted in several of the preceding sections, variable valvetrain technologies, downsizing and boosting, downspeeding, hybridization, and increased electrical and parasitic loads all act to increase the intake manifold pressure at a given vehicle load. The effect of this higher manifold pressure can be modeled for a single chemical species by the Antoine equation (Equation 14).

$$\mathbf{Log_{10}}\boldsymbol{P} = \mathbf{A - B / (T + C')} \qquad \mathbf{(14)}$$

Where: *P* is the vapor pressure (in bar)
T is the temperature (in Kelvin)
A, B, and C' are species-specific constants

This effect can be significant. Table 11 shows the impact of ambient pressure on the boiling point of two typical gasoline components, isooctane and ethanol.

Table 11: Approximate boiling points of isooctane and ethanol as a function of ambient pressure

Ambient Pressure (kPa)	Isooctane Boiling Temperature (°C)	Ethanol Boiling Temperature (°C)
10	34	31
50	80	60
100	99	78
200	124	91

While multicomponent gasoline mixtures are much more complicated and not easily modeled, the overall trend is that higher ambient pressures act to suppress fuel evaporation. In effect, an application with a higher intake manifold pressure for a given vehicle maneuver will require a lower DI (calculated using distillation data at standard atmospheric pressure) to achieve the same driveability performance.

Another way to look at the interaction between ambient temperature and pressure is through analysis of the "residence time" of the liquid fuel after an injection event. In this context, residence time is the duration for which a fuel droplet exists in the liquid phase before fully vaporizing. The data in Figure 17 was compiled by Parrish [44] using a GDI injector operating at 20 MPa fuel pressure. It shows that the fuel vaporization rate slows down at lower ambient temperatures and at higher ambient pressures (in the case of this study, the pressure inside the spray vessel is described in terms of air density, which is what the legend indicates in Figure 17). It is important to note for this discussion that the sensitivity to pressure becomes more significant at lower ambient temperatures. Engine technologies that tend to increase intake manifold pressure are more likely to impact driveability under cold conditions than at fully warmed-up operation.

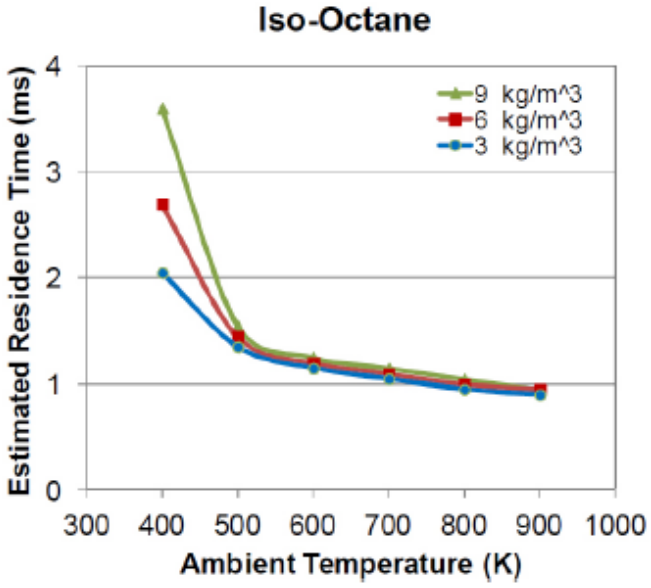


Figure 17: Example of fuel residence time as a function of ambient temperature and density at an injection pressure of 20 MPa [44]

Among the most significant technological changes in light-duty vehicles since the 1970's has been the introduction and continued refinement of electronic engine controls. These systems provide much more accurate control of parameters affecting driveability such as air/fuel ratio and ignition timing. Utilizing closed-loop feedback from exhaust oxygen sensors, modern systems use short- and long-term trim values to compensate for variations in factors such as injector flow rates and the stoichiometric air/fuel ratio of the fuel. This allows engines to tolerate, for example, variations in ethanol content while still maintaining precise, stoichiometric air/fuel ratio control. Of course, this control precision requires the O_2 sensor to be warmed up and generating a signal. For a cold start, when DI is most important,

the O_2 sensor is cold and the control system is blind or using data remembered from previous operation.

Some advanced control systems even include the ability to "sense" driveability issues – generally through analysis of the engine flywheel rotational speed fluctuations – and, in theory, compensate fueling rates to account for poor vaporization of high DI fuels during cold start and warm-up operation. As covered in the following section, though, this DI adaptation capability can only compensate up to a point.

Emissions Requirements

As noted earlier, the fundamental, underlying cause of driveability issues when the fuel DI is too high is that there is insufficient fuel vaporization resulting in a lean air/fuel ratio in the combustion chamber. One logical solution to this is to simply inject more fuel such that the resulting amount of vapor is sufficient to sustain robust combustion. The amount of enrichment that can be utilized, though, is ultimately constrained by emissions regulations.

While emission standards are not explicitly tied to ASTM D4814, which is a performance specification, they are inherently linked due to the effects of changing fuel volatility on both driveability and emissions. ASTM D4814 regulates the fuel volatility to an allowable limit and auto manufacturers are then responsible for engineering and calibrating vehicles that can maintain good driveability with these fuels. The auto manufacturers, though, are also responsible for meeting the emission standards set by the EPA. The inherent link from ASTM D4814 to emissions standards is therefore made by the automotive industry. If DI requirements were relaxed allowing a wider range of fuel volatility, automotive manufacturers would have more difficulty simultaneously meeting emissions and driveability targets. Conversely, if emissions standards were removed or relaxed, vehicle manufacturers could, in theory, increase enrichment during cold start and warm up, and DI requirements could be relaxed. This linkage is further explained below.

Federal and state regulations place limits on a range of emissions constituents including hydrocarbons (HC), carbon monoxide (CO), and oxides of nitrogen (NO_x) – either directly or indirectly through fuel economy targets (which control CO_2 emissions). HC emissions standards, in particular, have become more stringent by several orders of magnitude since DI was first investigated. From 1969 to 2017 the allowable HC emissions of the FTP-75 drive cycle dropped from 6.3 to 0.03 g/mile as shown in Figure 18 on a logarithmic scale [45, 46]. The 0.03 g/mile limit for the end of the Tier 3 standards is for HC (NMOG) and NO_x combined making the requirement even more stringent. Future emission standards may require fleet averages to be lower than 0.03 g/mile. This represents over a two order of magnitude reduction in the allowable level since fuel DI was initially investigated. And the current limits

are a full order of magnitude lower than in 2000 when the current DI calculation and limits (without the ethanol correction) were adopted into ASTM D4814.

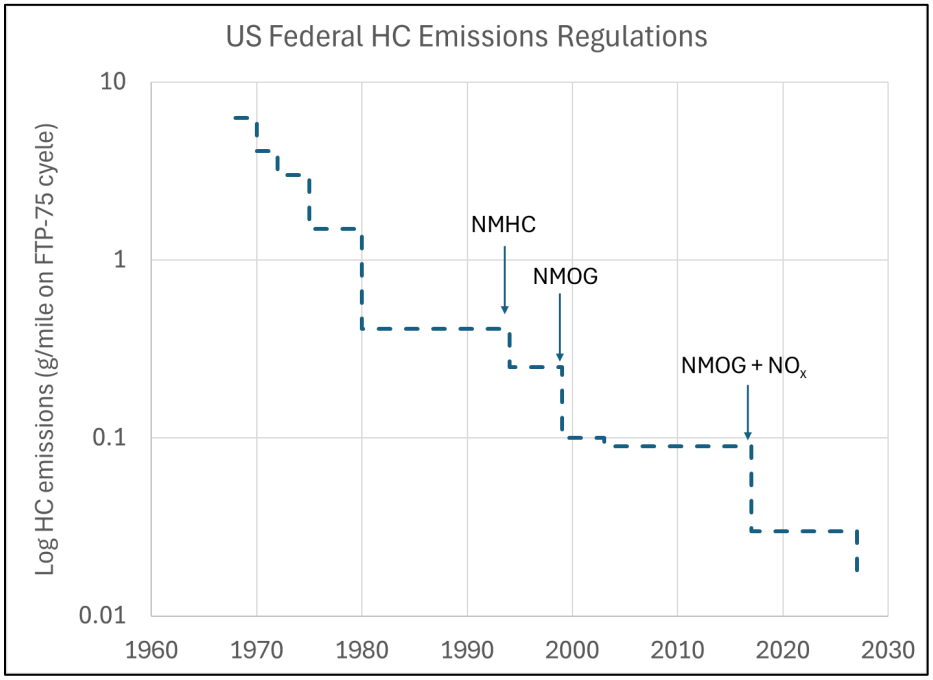


Figure 18: US Federal HC emissions regulations from 1968 to present [45, 46]

Regulated levels for CO emissions and particulate matter have also decreased significantly in that timeframe as shown in Figure 19 [45, 46].

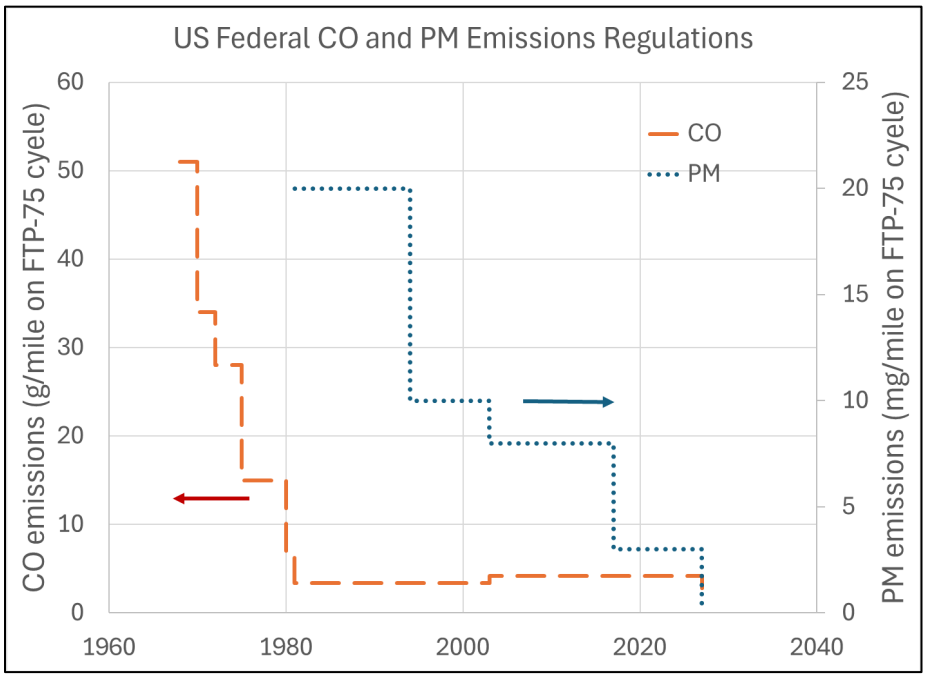


Figure 19: US Federal CO and PM emissions regulations from 1968 to present [45, 46]

Modern light-duty gasoline vehicles utilize three-way catalytic converters to control HC, CO, and NO_x emissions. These systems are capable of very high exhaust emissions conversion efficiency for all three constituents as long as two criteria are met: 1) the exhaust mixture passing through the catalytic converter must be stoichiometric and 2) the catalyst must be above its critical "light-off" temperature. When the engine and vehicle are first started, the catalytic converter is cold and the constituent emissions pass through with relatively low conversion rates.

If the vehicle is "over fueled" in order to generate sufficiently rich mixtures for good combustion with higher DI fuels two issues occur. The first is that any excess liquid fuel entering the combustion system that did not evaporate prior to combustion will vaporize when exposed to the high temperatures from the combustion process. These will then leave in the exhaust as unburned HC emissions, or if they do partially oxidize, CO emissions. In the initial few seconds of operation, when the catalytic converter is still below the light-off temperature, these contribute directly to tailpipe HC and CO emissions.

The second issue is that even when the catalytic converter is at a high enough temperature to support oxidation of the HCs, the conversion efficiency will be very low when the exhaust is richer than stoichiometry as shown in Figure 20.

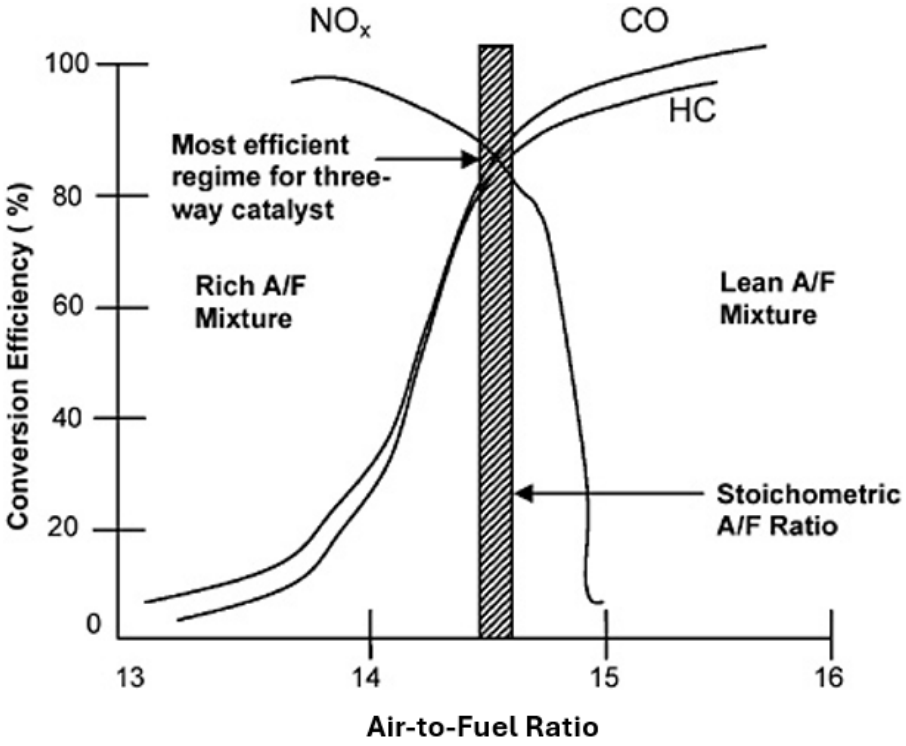


Figure 20: Catalytic converter efficiency as a function of Lambda [47]

These constraints are more severe as the fuel injection location moves closer to the cylinder, or even into the cylinder in the case of GDI. For systems injecting further upstream, the excess, higher boiling point components can accumulate as fuel "puddles" and not lead as directly to rich exhaust mixtures and unburned HCs. But these systems are more challenging for controlling air/fuel ratio during transient operation due to the changing intake manifold pressure and its effect on volatility.

A more significant constraint for GDI engines, though, is particulate matter emissions. A major source of particulate mass or particulate number emissions is the occurrence of diffusion flames on the surface of liquid fuel drops or puddles. In the case of PFI, most of the excess fuel injected to overcome poor vaporization during cold starts accumulates in the intake port. For GDI fuel systems, any excess fuel injected will tend to accumulate on the combustion chamber surfaces such as the piston and can be a significant contributor to PM emissions.

Summary

The impact of modern engine technology on sensitivity to fuel volatility metrics such as DI is complex with both benefits and detriments in many cases. The technology having the greatest impact is the shift from carburetors to port fuel injection to direct injection. With each change the engine has become more robust to fuel volatility since the smaller droplets and higher ambient temperature environment allow for greater rates of evaporation. This reduces the amount of enrichment or over-fueling required for a given fuel DI in order to achieve rich enough vapors for good combustion and driveability. In theory, this would allow modern vehicles to tolerate fuels with higher DI at the levels of enrichment used in the past. These benefits are counteracted, though, by increasingly stringent emissions regulations that limit the amount of enrichment that is permissible.

Based on interviews with subject matter experts (SMEs), J. Michael Gwidt (fuel control expert at General Motors) noted that "DI systems, due to their improved atomization and vaporization at high pressure, generally require less enrichment adjustment to compensate for fuel property variations [48]." But this reduction in required enrichment is offset by a more direct impact of any over fueling on HC, CO, and PM emissions during cold starts.

Rafat Hattar, GM Technical Fellow, Gasoline Exhaust Emissions Controls, noted that "With GDI, mixture preparation is generally more robust, so sensitivity to fuel volatility is reduced relative to a pure PFI system. However, PM constraints have driven many programs toward PFDI architectures, where PFI is used during catalyst light-off and selected operating zones.

In those conditions, some of the original PFI-type sensitivity to fuel volatility is re-introduced, so volatility remains an important fuel parameter even in the GDI era [49]."

Another concern that was raised repeatedly during the SME interviews was the impact of any potential changes to the legacy vehicle fleet and the impact of future, more stringent emissions standards. Beth Raney-Pablo, VPSE Senior Engineer, Fuels at Ford, noted, "tightening emission standards make it harder for us to meet the emission standards. We have to make changes to the vehicle hardware, engines in order to meet those. We need fuel changes in order to enable us to meet those emissions. And anything that widens regulations on the fuels makes that job harder [50]." Matt Schnabelrauch of GM added that "So far we've been able to balance high-DI fueling performance with emissions requirements, but… the tighter Tier4/LEV4 particulate requirements and NOx & hydrocarbon reductions… will impact those optimizations [51]."

Another common theme in the SME interviews with OEM calibrators and fuel control experts was that variation in the fuel volatility or distillation curves is a continuing issue regardless of the engine technology. GM's Michael Zumbaugh stated that, "When you develop a control system to be rich enough to run on high DI fuel, you have to carry that penalty over to any emissions open loop fueling strategy which doesn't otherwise need the extra fuel [52]", emphasizing that it is a challenge to cover a wide range of DI and meet both emissions and driveability over the whole range.

Existing evaluations of the impact of modern engine technology on driveability and the sensitivity to fuel DI are difficult to interpret. The comparisons are not just between PFI and GDI fuel systems, or naturally aspirated versus downsize boosted engines, but are comparing different vehicles from different manufacturers with different control architectures and calibration strategies and goals. Ultimately, more detailed experimental investigations are required to fully understand the net benefit of modern engine technology such as GDI, variable valve actuation, downsize boosting, and hybridization on the sensitivity to fuel volatility in general and DI specifically.

Gasoline Production, Distribution, and Regulatory Context

To properly evaluate fuel quality specifications such as ASTM D4814 and its parameters including the Driveability Index (DI), it is necessary to understand how gasoline is manufactured, distributed, and regulated within the United States. Gasoline is produced and delivered through a multi-stage supply chain, with regulatory authority and specification enforcement applied at different points along this process.

Gasoline Production and Distribution Process

As shown in Figure 21, gasoline production begins with the delivery of crude oil to a refinery via ship, rail, or pipeline. At the refinery, crude oil is then processed into multiple hydrocarbon streams, which are subsequently blended to produce the required gasoline blendstocks. Certification of fuel properties occurs at the refinery prior to shipment, based on the intended downstream blending and finished fuel requirements.

In most cases in the US, the product leaving the refinery is not a finished gasoline but a blendstock for oxygenate blending (BOB). BOBs are formulated to be blended downstream with ethanol, deposit control additives, and in some cases butane, at distribution terminals. Once produced, a sample of the BOB is first taken and hand-blended with the intended future ethanol concentration to create a representative sample of the finished fuel that will be produced downstream. This sample is tested and certified at the refinery where it must meet ASTM D4814 specifications, federal standards, and any applicable state and pipeline requirements. The ethanol free BOB is then transported often through petroleum pipelines where it must meet both federal gasoline standards and comply with the pipeline standards. The BOB then makes its way to regional distribution terminals where it will become a finished fuel. Ethanol is not transported in pipelines due to its affinity for water and associated contamination risks and is instead delivered separately by rail, truck, or barge to distribution terminals for blending.

At the terminal, BOBs are blended with ethanol and other components to produce finished gasoline that meets applicable federal and state requirements. The finished gasoline is then transported by truck to retail outlets for sale to consumers. Fuel quality specifications are generally enforced upstream of the retail point, placing compliance responsibility on refiners and terminal operators.

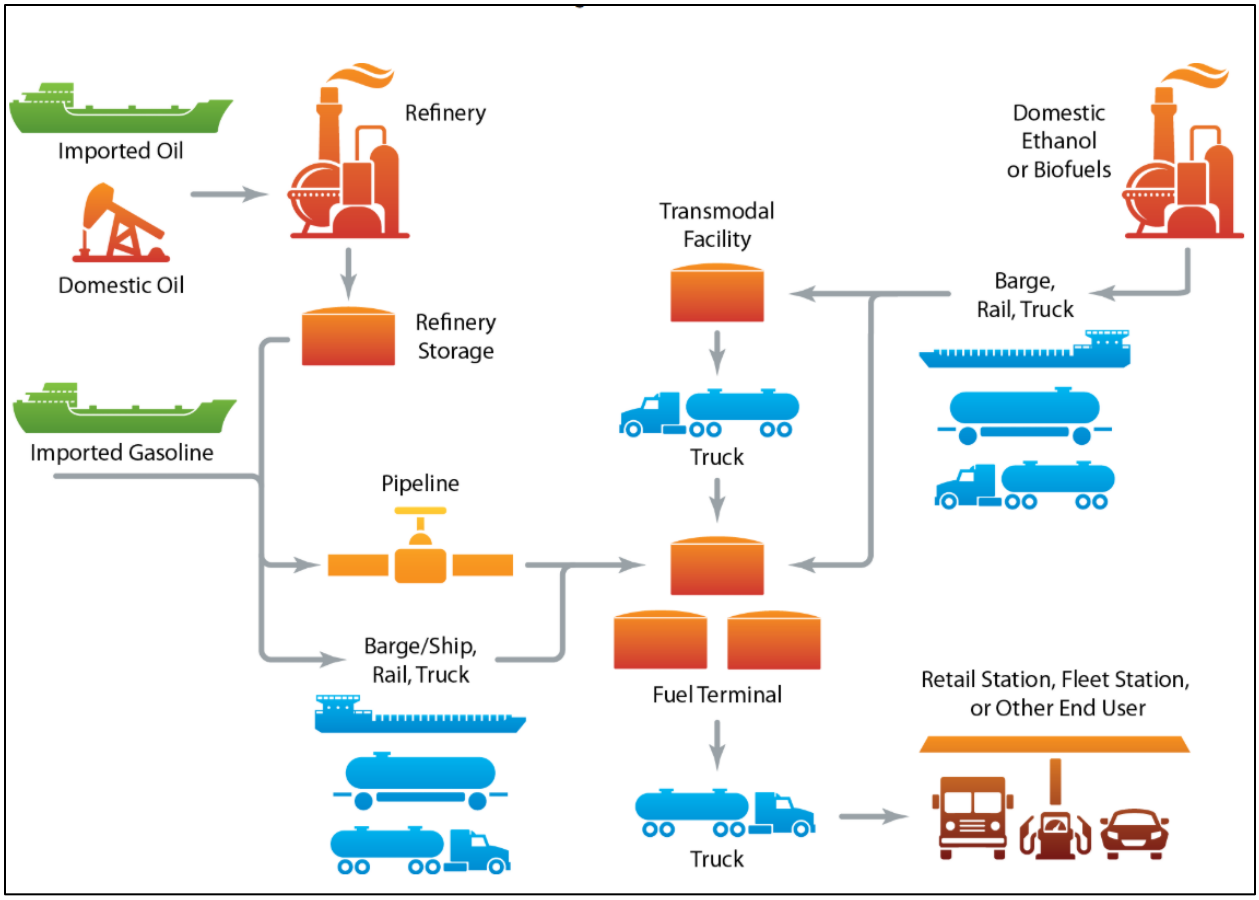


Figure 21: Schematic of Fuel Distribution System

Fuel Volatility Properties and their Impact on Driveability Index

Driveability and DI are impacted by a multitude of fuel parameters like the distillation temperatures of the fuel, the vapor pressure as well as the percentage of ethanol mixed with gasoline. This section takes a detailed look at these parameters.

Distillation Curve

Distillation testing is a test method used in the petrochemical industry to determine the quantitative and qualitative details about the volatility of a mixture of hydrocarbons in fuels [53]. The distillation curve is the graph obtained through the distillation process which provides information on the fraction of the mixture that evaporates at specific temperatures. The distillation curve for a mixture is obtained using the process described in the ASTM D86 standard [53]. The distillation curves for the median DI gasolines in the US for summer and winter are shown in Figure 22. The x-axis provides Txx values, which is the temperature at which xx% of the fuel has evaporated. A distillation process is used to determine critical distillation temperatures such as T10, T50 and T90, which are critical for cold start and warm-up driveability. These values are used in the Driveability Index (DI) model, shown in Equation 1 and Equation 2, to determine the DI value. ASTM D4814 stipulates the limits for the critical distillation temperatures and DI.

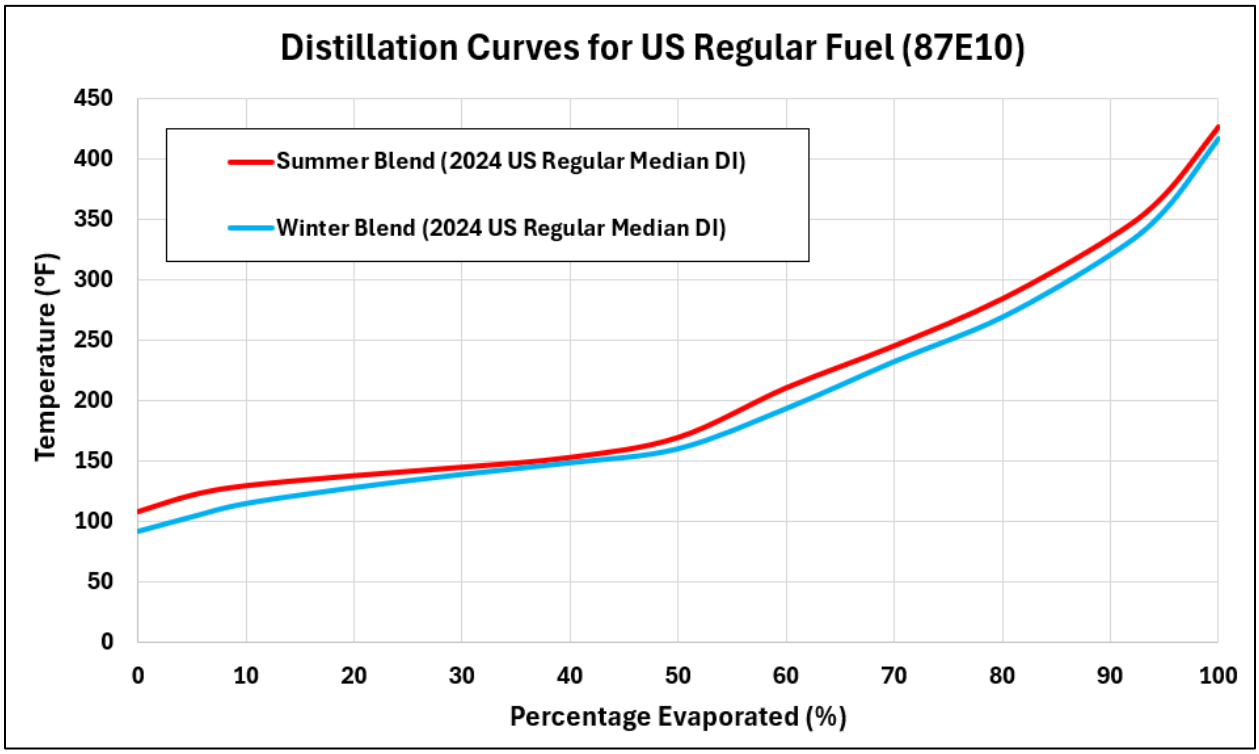


Figure 22: Distillation curves for median DI gasoline samples from the United States for summer and winter (2024)

The axes in Figure 22 can be switched to have the temperature on the x-axis and percentage of fuel vaporized on the y-axis to show a temperature-evaporation curve. This is shown in Figure 23. This graph provides Exx values, which is the percentage of fuel that has evaporated at a temperature of xx°C (or xx°F). The EN 228 standard, which is used in United Kingdom (UK) and the European Union (EU), uses Exx values to set gasoline standards.

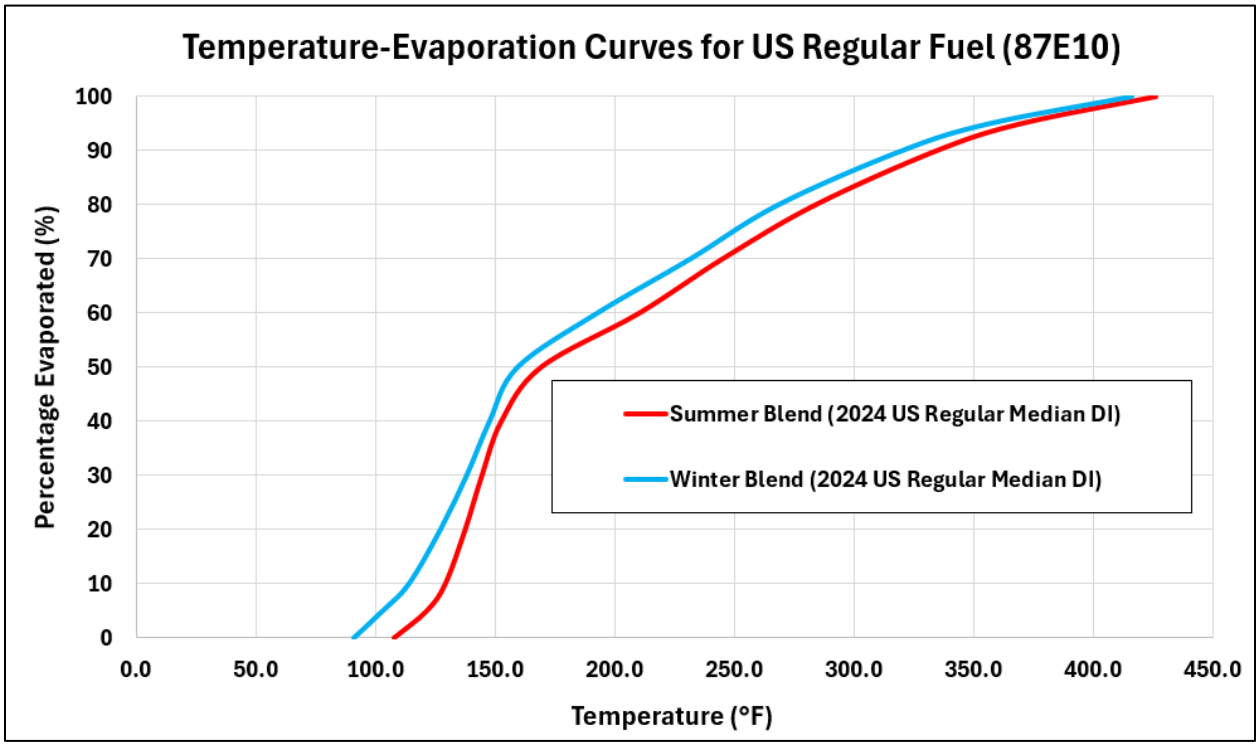


Figure 23: Evaporative curves for median DI gasoline samples from the United States for summer and winter (2024)

All early driveability models developed either with data obtained through CRC program or company specific models used either Txx or Exx values.

As mentioned above, the distillation curve is determined using the procedure detailed in the ASTM D86 standard or the ASTM D7345 standard (ASTM D4814 mentions both procedures as acceptable for calculating the distillation temperatures). A summary of the procedure as mentioned in the standard is included in the Appendix.

Vapor Pressure and Its Impact on Driveability

Vapor pressure is the pressure exerted by the vapor molecules of a substance when the vapor and liquid phases are in equilibrium. Vapor pressure is a function of temperature,

pressure as well as the volatility of the liquid. For a given temperature, a liquid with higher volatility will have more molecules in the vapor phase, thus exerting a higher pressure.

There are two metrics for vapor pressures associated with gasoline

1. **Reid Vapor Pressure (RVP)**
2. **Dry Vapor Pressure Equivalent (DVPE)**

RVP is marginally higher than DVPE because of the process of measurement [54]. Both vapor pressures are measured at 100°F. The EPA regulates summertime RVP of fuels (from the 1st of May to the 15th of September [55]), while ASTM D4814 has DVPE limits based on the grade of gasoline. RVP was replaced by DVPE in ASTM D4814 as RVP is not as reproducible and is not applicable to fuels containing oxygenated compounds other than methyl t-butyl ether (MTBE). Footnote B (included below) in Table 1 of ASTM D4814-25 states this regarding vapor pressure:

B **Consult EPA for approved test methods for compliance with EPA vapor pressure regulations.**

However, it should be noted that RVP and DVPE are often used interchangeably. This was confirmed in discussions with Jim Anderson [56] and Scott Bohr [57] from Ford Motor Company. Mr. Bohr said in his experience, the industry uses the term 'RVP' but measures 'DVPE'. The DVPE is calculated using the procedure outlined in ASTM D5191, which is the method adopted by the EPA for its RVP regulatory requirements. The experimental procedure outputs the total vapor pressure. The DVPE is calculated using the correlation shown in Equation 15.

$$\text{DVPE (kPa)} = 0.965x(\text{Total Vapor Pressure}) + 3.78 \quad (15)$$

A summary of the procedure to measure the total vapor pressure as included in ASTM D5191 is included in the Appendix.

Vapor pressure is an important property of commercial gasoline and determines the performance of a fuel under different ambient and engine operating conditions. A high vapor pressure in hot weather or at high altitude (low atmospheric pressure) can lead to issues such as vapor lock. It can also lead to increased evaporative emissions. Certain areas in the United States are required to sell reformulated gasoline (RFG) to reduce emissions of smog-forming and toxic pollutants [58]. EPA requires the summertime vapor pressure for RFG to be lower than 9 psi. Depending on the volatility class, the summer vapor pressure

requirement for RFG is a maximum of 7.4 psi for volatility class AAA gasoline and 7.8 psi for volatility class AA gasoline.

In cold weather and at low altitudes, a higher vapor pressure ensures ease in starting the vehicle. ASTM D4814 restricts the minimum T50, DVPE at 37.8°C (100°F) and $T_{V/L=20}$ to ensure that the fuel is not excessively volatile.

When ethanol is mixed with gasoline, the vapor pressure of the resulting mixture is higher than the vapor pressure of either the base hydrocarbon blend or the ethanol. The hydrocarbon blendstock and ethanol form an azeotrope, the vapor pressure of which peaks between 0 to 5% of ethanol by volume. As additional ethanol beyond 5% is added to the fuel, the vapor pressure gradually decreases. This is shown below in Figure 24 [59] although the peak RVP at 5% as data was not taken at this concentration. Because of the higher vapor pressure of the E10 blends, the fuel was granted a 1 psi vapor pressure waiver by Congress in 1990. This facilitated the use of the then available finished gasolines in blending E10.

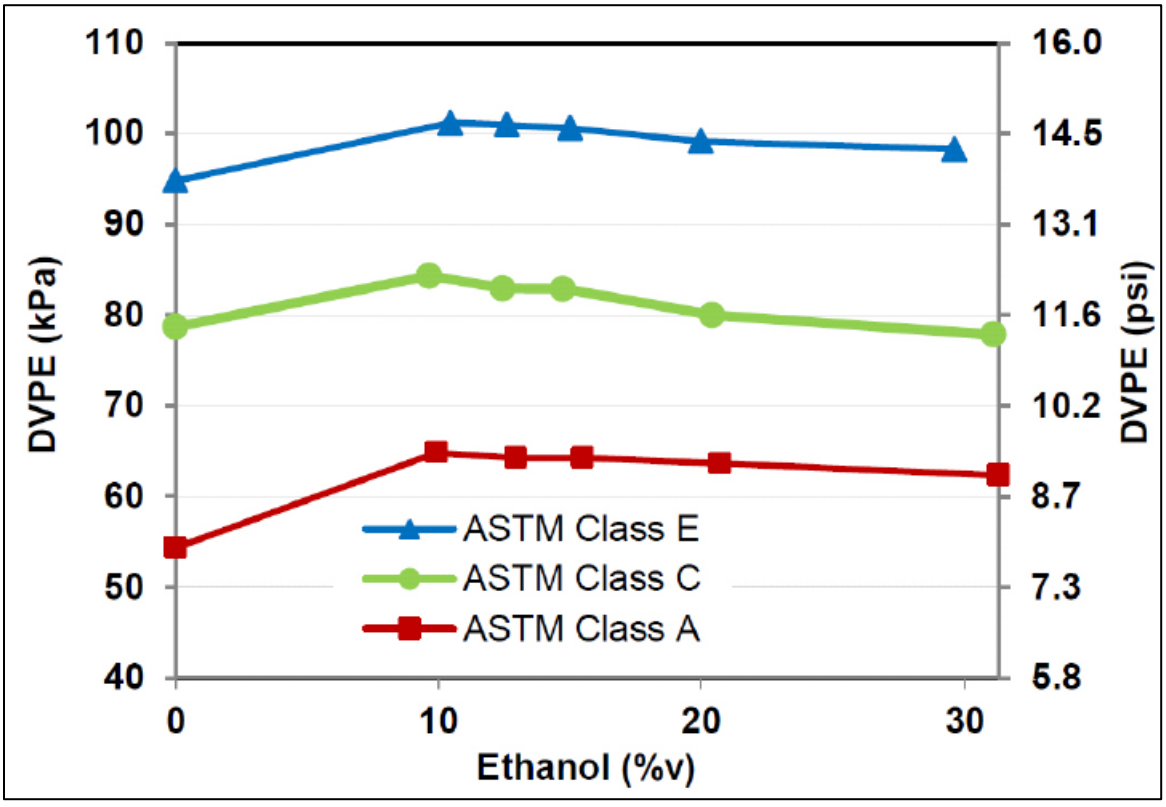


Figure 24: Change in gasoline DVPE with ethanol content [59]

DVPE shows an inverse correlation with $T_{V/L=20}$. As the vapor pressure of the fuel increases, the temperature at which a vapor to liquid volume ratio is 20:1 decreases, which is why the

inverse correlation exists between the two parameters. This inverse correlation is shown in Figure 25.

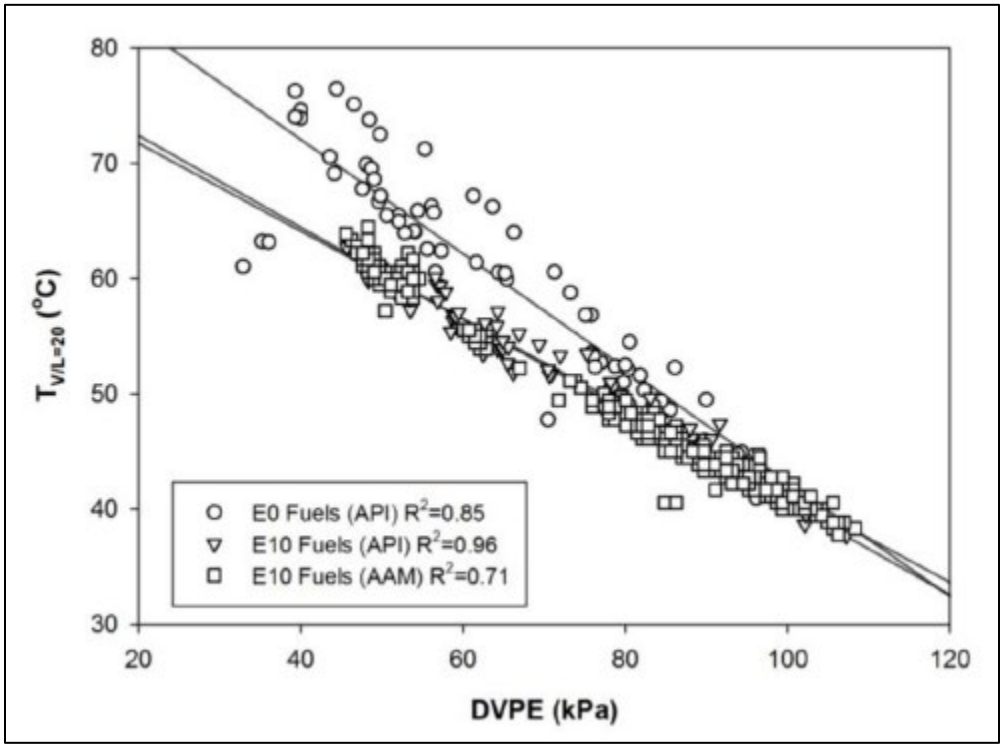


Figure 25: $T_{V/L=20}$ versus DVPE for E0 and E10 fuels [11]

In cold start and warm-up driveability studies conducted by the CRC through the years, vapor pressure has not shown a strong correlation with trained rater demerits. This was evaluated in the first cold start and warm-up driveability study in 1968, which concluded that RVP did not impact driveability.

A CRC study conducted in 2008 [60] analyzed the impact of DVPE on cold start and warm-up driveability. Vapor pressures (DVPE) of the five tested fuels varied: the two E0 gasolines had DVPEs of 41 and 56 kPa (5.9 and 8.1 psi), the E15 blends were 49 and 69 kPa (7.1 and 9.9 psi), and the E20 had a DVPE of 49 kPa (7.1 psi). Testing was conducted at three nominal temperatures approximately -5°C, 1°C, and 8°C and thus focused on summertime volatility fuels tested at cold to intermediate temperatures. No statistically significant impact on cold weather driveability was found with changes in vapor pressure of the fuels or the amount of ethanol included in the fuel.

The only study which reported a dependency of cold weather driveability demerits on DVPE was a CRC study on flex fuel vehicles [61] in 2008, that tested E75 and E85 fuels with different DVPE values at varying ambient conditions. The study developed a driveability model

correlating TWDs with five variables, of which DVPE was one. The model is shown by Equation 16.

Ln TWD = -3.994-0.2507xTemp in C + 0.00598 x DVPE in kPa + 0.0829xEtOH in % + 0.0023xDVPE in kPa x Temp in C (16)

DVPE has shown to have better direct correlations with demerits for hot weather driveability. In a 2001 CRC Hot Fuel Handling study [15], a better prediction of ln TWD was obtained by using DVPE (R^2 =0.73, p-value = 0.00044) as compared to T50 (R^2=0.39). $T_{V/L=20}$ showed a similar correlation with the demerits as DVPE. The study used vehicles with sequential fuel injection (SFI) and port fuel injection (PFI), but no carbureted vehicles. Similar conclusions can be drawn from the Hot Fuel Handling programs from 2010 [62] and 2014 [7]. The most recent study on hot fuel handling [7] did note that port fuel injection (PFI) vehicles had statistically significantly higher TWD than spark ignition direct injection (SIDI) vehicles.

The impact of vapor pressure on Driveability Index comes from the constraint put on the fuel companies by having to abide by vapor pressure and DI limits. Based on discussions with oil company personnel, this is predominantly a summer issue. With the exception of Alaska and Hawaii, all other states in the United States use volatility classes A, AA or AAA gasoline for the summer months of May to mid-September. The maximum DVPE of grade A gasoline is 9 psi (7.4 psi for class AAA and 7.8 psi for class AA). The challenge for the refineries is keeping the DI below the 1250°F limit for the classes A, AA and AAA gasolines while also ensuring the DVPE does not exceed its maximum limit.

There is a delicate balancing act here, as maintaining the DI below 1250°F requires a certain amount of high volatility components, but the front-end volatility cannot be too high to keep the DVPE in check.

This is more challenging for premium fuel (for example, 93 AKI). The higher AKI value for premium fuel is achieved by adding high octane aromatics such as toluene, xylene and trimethyl-benzene [63], or iso-paraffins from alkylate, or both. High molecular weight aromatics increase the T50 and T90 of the fuel. DI compliance cannot be achieved simply by balancing the low volatility aromatics with high volatility paraffins, as they can raise the vapor pressure above the regulatory limit. The fuel needs to have a fine balance of hydrocarbons to ensure compliance with both parameters. Figure 26 shows the distillation curves for the summertime median samples for US 87E10 regular fuel (DI=1065°F) and US 93E10 premium fuel (DI=1142°F) for the year 2024. The premium fuel has a 33°F higher T50 than the regular fuel, which increases its DI. Both fuels have an initial boiling point above 100°F, which is the temperature at which DVPE is measured to ensure the vapor pressure is within the EPA

regulatory limit, although it should be noted that distillation temperatures are measured at atmospheric pressure while DVPE is measured in a vacuum.

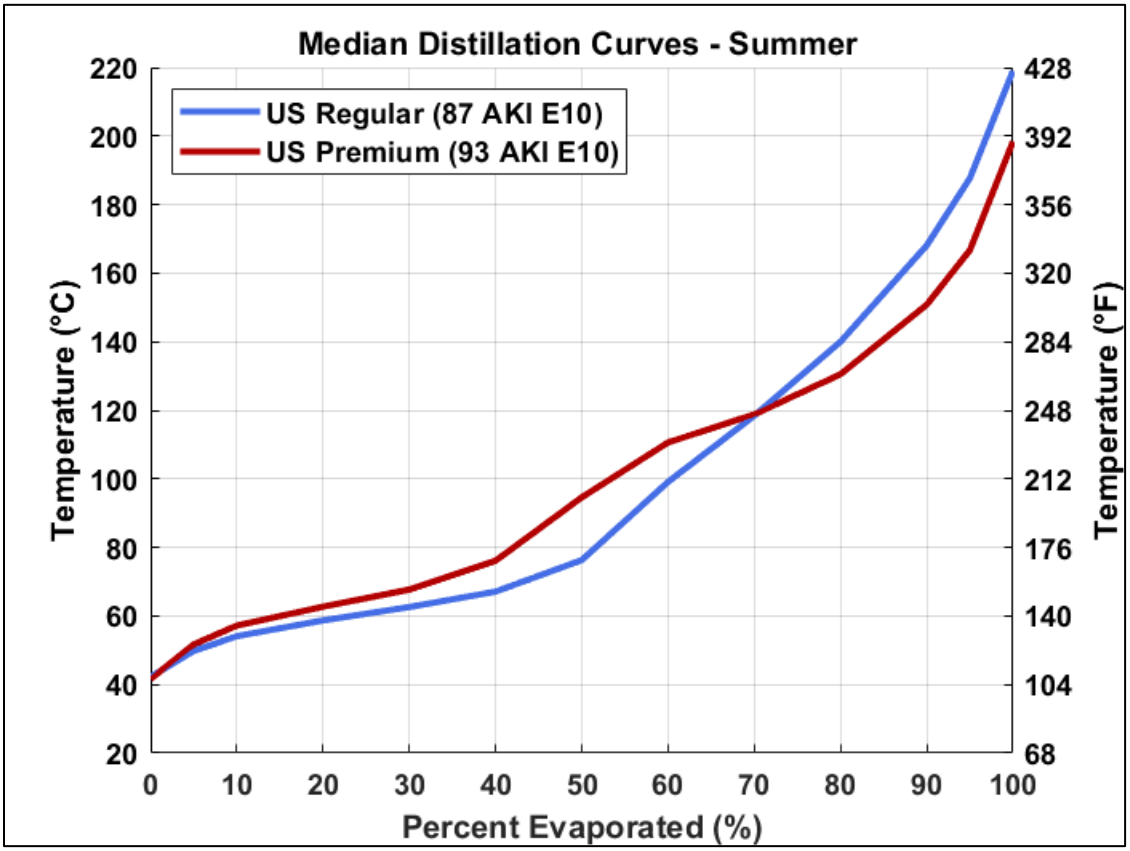


Figure 26: Median DI distillation curves for US regular and US premium gasoline samples (summer 2024)

As pointed out, vapor pressure does not have a direct impact on the Driveability Index (DI). However, conformance to vapor pressure impacts the hydrocarbons that are included in the fuel, which affects the distillation temperatures and hence, DI. Discussions with fuel experts brought up many interesting points regarding vapor pressure, which are stated below.

In a discussion with Bill Studzinski (formerly of General Motors), he mentioned that the vapor pressure limits were put in place in the 1970s based on carbureted vehicle performance, and that modern vehicles with PFI and GDI fuel systems could perform without driveability issues with lower winter vapor pressure limits (the maximum vapor pressure limit during the winter is 16 psi for grade E gasoline). He noted that even though China is a vast country with many different climate regions, they only use two vapor pressure values depending on the time of the year and location. This is not to imply that only two vapor pressure values are sufficient, but more so to point to the fact that perhaps the vapor pressure limits instituted in the days

of carbureted vehicles in the 1970s could be reevaluated with modern fuel systems like PFI and GDI in mind. Mr. Studzinski pointed out the challenge fuel manufacturers face in meeting the vapor pressure limits in the summer. The fuel manufacturers cannot use the lighter hydrocarbons, and storing them for use in the winter poses an additional challenge. The US has a surfeit of butane and pentane due to fracking and the market is gasoline and petrochemicals, while China uses butane as cooking fuel and pentane for petrochemicals so they strip them from the gasoline. This difference between the two countries came up during discussions with Dr. Pat Geng and Dr. Coleman Jones.

Former EPA director of fuels policy, Paul Machiele, said that the data suggests that having an RVP lower than 9 psi is often no longer beneficial (the RVP is 7.4 psi for RFG) [30][7]. Mr. Machiele said that with experimental testing and analyzing past data, the case can be made that a 9 psi RFG might provide better overall emission performance. This can justify further relaxing RFG vapor pressure to 9 psi. The emission controls on modern vehicles are much better than when the requirement was put in place.

Russ Lewis (Marathon) [64], Dr. Jim Simnick [26] and Matt Sheehan (Chevron) [65] all expressed the same difficulties of removing the lighter paraffins like butanes and pentanes from the summertime gasoline blends to meet the RVP requirements, especially for RFG. Mr. Sheehan stated that more than DI limits, the challenge is not exceeding the RVP limits. He also mentioned that the high RVP limits (16 psi for volatility class E gasoline) in the winter permit fuel manufacturers to use all the light hydrocarbons stored during the summer.

Vapor-Liquid Ratio Temperature ($T_{V/L=20}$)

In the days of carbureted engines, vapor lock was a major issue for hot weather driveability. Vapor lock occurs due to the premature vaporization of the fuel in the fuel line, which reduces fuel pressure and starves the engine of fuel because the fuel system is designed to deliver a liquid, not gas to the air mixing equipment. This reduces the ability for the engine mounted pump to suck fuel from the tank. This can cause driveability issues such as stalling or rough idling. In modern vehicles with PFI or GDI fuel systems, vapor lock is not a common issue as the fuel in the fuel line is pressurized to around 300 kPa to 400 kPa, which helps resist vaporization. However, vapor lock can still occur for volatile fuel blends exposed to excessive heat. As vehicles have evolved, the location of vapor formation has moved from the fuel line to the fuel rail, which is mounted on the hot engine.

[7] Certain other areas such as Southeast Michigan, which is not an RFG area, require low vapor pressure fuel (7 psi or less) from June 1st to September 15th to reduce smog.

ASTM D4814 includes a vapor lock protection class through a vapor-liquid ratio temperature limit, or as abbreviated a $T_{V/L=20}$ limit. $T_{V/L=20}$ is the temperature at which the vapor-to-liquid ratio of a fuel is 20:1 as measured by the procedure described in ASTM D5188. The higher the volatility of the fuel, the lower its $T_{V/L=20}$ value. A fuel with a lower $T_{V/L=20}$ is more susceptible to vapor lock.

ASTM D5188 [66] defines $T_{V/L=20}$ as follows:

$T_{V/L=20}$ – The equilibrium temperature at which the partial pressure of a sample under test conditions is equal to 101.3 kPa (14.69 psia) and the vapor-liquid ratio is 20.

A summary of the test method as mentioned in ASTM D5188 to determine the $T_{V/L=20}$ of a sample is included in the Appendix.

ASTM D4814 specifies six vapor lock protection classes that restrict the $T_{V/L=20}$ to a certain minimum value. The vapor lock protection class requirements are shown in Table 12.

Table 12: Vapor lock protection class requirements [5]

	Vapor Lock Protection Class					
	1	2	3	4	5	6
Temperature, °C (°F) for a Vapor-Liquid Ratio of 20, min	54 (129)	50 (122)	47 (116)	42 (107)	39 (102)	35 (95)
Special Requirements for Area V of D4814 Temperature, °C (°F) for a Vapor-Liquid Ratio of 20, min	54 (129)	50 (122)	47 (116)	47 (116)	41 (105)	35 (95)
[A] See 1.7 for determining conformance with numerical specification limits in this table. When using this table to determine the conformance of the temperature for a vapor-liquid ratio of 20, the reader is advised to review other applicable national, state, provincial, or local requirements (for example, EPA's "Substantially Similar" rule, CARB regulations, and other local regulations. [B] Gasoline, or blend of oxygenate and gasoline as sold to the consumer, shall meet these limits. Certain gasolines meeting these limits of this table may not be suitable for blending with ethanol. [C] Gasolines and gasoline-oxygenate blends sold at retail sites located in Area V shown in Fig. X1.2 (generally high elevations) shall use the special limits shown in Row 2 of this table, regardless of ethanol content.						

Along with the grade of gasoline (from A to E), a vapor lock protection class is also specified for the fuel depending on the state and the time of the year. A fuel with high $T_{V/L=20}$ is specified for high ambient temperatures. Conversely, for low ambient temperatures, a fuel with low $T_{V/L=20}$ is specified. With six classes for volatility and vapor lock each, a total of 36 theoretical combinations are possible. However, the high volatility grade gasolines (like classes D and E used in the winter) are paired with the vapor lock protection classes low $T_{V/L=20}$ values, while the low volatility classes (like classes A and B used in the summer) are paired with the vapor lock protection classes with high $T_{V/L=20}$ values. ASTM D4814 has a table for the volatility and vapor lock protection class combination for each state, for each month (Table 4 in ASTM

D4814-25). There are a total of 12 combinations in this table for volatility and vapor lock classes.

The schedule for the US seasonal and geographical volatility classes for the states of Alaska, California, Hawaii, Michigan, and Texas is shown below in Table 13 (refer to ASTM D4814 for the schedule for all US states). The table shows the combinations of volatility and vapor lock classes based on states and the month. When seasonal temperature changes are modest, only the vapor-lock class shifts while the volatility class remains unchanged (for example, in Colorado going from July to August). For certain months, multiple classes might be stated depending on how much impact the change in weather can have on driveability.

Table 13: Schedule of U.S. Seasonal and Geographical Volatility Classes [5]

State	Jan	Feb	Mar	Apr	May [B]	June	July	Aug	Sept 1-15	Sept 16-30	Oct	Nov	Dec
Alaska	E-6	E-6	E-6	E-6	E-6/D-4	D-4	D-4	D-4	D-4	D-4/E-6	C-3	C-3/D-4	D-4
Colorado [C]	D-4	D-4/C-3	C-3	C-3/A-3	A-2 (C-3)	A-1	A-1	A-2	A-2	A-2/B-2	B-2/C-3	C-3/D-4	D-4
Hawaii	C-3	C-3	C-3	C-3	C-3	C-3	C-3	C-3	C-3	C-3	C-3	C-3	C-3
Michigan [C]	E-5	E-5	E-5/D-4	D-4/A-4	A-4 (D-4)	A-3	A-3	A-3	A-3	A-3/D-4	D-4	D-4/E-5	E-5
Texas [C] (E 99° Longitude)	D-4	D-4/C-3	C-3	C-3/A-2	A-2 (C-3)	A-2	A-2	A-2	A-2	A-2/B-2	B-2/C-3	C-3/D-4	D-4
Texas [C] (W 99° Longitude)	D-4	D-4/C-3	C-3/B-2	C-3/A-2	A-2 (B-2)	A-1	A-2	A-2	A-2	A-2/B-2	B-2/C-3	C-3	C-3/D-4

[A] For the period May 1 through September 15, the specified vapor pressure classes shall meet U.S. EPA volatility regulations. Reformulated gasoline is limited to a maximum vapor pressure of 7.4 psi during the summer EPA regulatory control period. Under EPA regulations at 40 CFR 1090.215(b), from May 1 through September 15, certain gasoline-ethanol blends in conventional gasoline areas are allowed a 1.0 psi higher vapor pressure. Other requirements apply to the ethanol waiver. See Appendix X3 for additional U.S. federal volatility and other regulations. The 1.0 psi vapor pressure waiver for gasoline-ethanol blends is not incorporated into Specification D4814. Many states provide a 1.0 psi vapor pressure waiver for gasoline-ethanol blends; however, vapor pressure limits for gasoline-ethanol blends vary among states and in areas with Federally approved State Implementation Plans (SIPs). Contact specific states to determine their vapor pressure limits for gasoline-ethanol blends.
[B] Values in parentheses are permitted for retail stations and other end users.
[C] See Tables 5-7 for specific area requirements. Consult U.S. Environmental Protection Agency regulations under 40 CFR Part 1090 for Federal 7.8 psi vapor pressure areas, RFG covered areas, and Federally approved SIP areas.

While $T_{V/L=20}$ is a part of the volatility specification for gasoline in the United States, studies have not shown it to have an impact on cold start and warm-up driveability.

An argument can be made that with all modern gasoline vehicles being either PFI or GDI with pressurized fuel lines, $T_{V/L=20}$ is no longer a necessity. Russ Lewis is of the opinion that having

$T_{V/L=20}$ limits along with DVPE over constrains the production of gasoline. $T_{V/L=20}$ has shown a strong correlation with DVPE and T10 [11], meaning the three parameters are not independent, and limits on the DVPE and T10 are sufficient to ensure vapor lock protection. Bill Studzinski mentioned that the plethora of vapor lock classes and hence, volatility – vapor lock class combinations, are an artifact of the 1970s, which was when the limits were put into place and the majority of engines were carbureted. Evaporative emissions expert Scott Bohr (Ford) made a case for $T_{V/L=20}$, stating that the parameter is useful for the evaluation of the evaporative emissions system on a vehicle.

Europe uses Vapor Lock Index (VLI) for vapor lock protection. VLI, shown in Equation 17, is a combination of DVPE and E70.

$$\mathbf{VLI = 10 \times DVPE\ (kPa) + 7 \times E70\ (\%)} \quad \mathbf{(17)}$$

VLI does put additional constraints on the gasoline. If the maximum permissible values of DVPE and E70 are used, the VLI value does exceed the maximum permissible limit for all four classes which have VLI associated with them. This is what the EN228 standard states about VLI.

Each country shall apply one or more volatility classes (Class C1, D1, E1, or F1) with vapor lock index (VLI) for the transition periods on either side of summer. Each transition period shall be a minimum of four weeks. When transition periods are deemed critical, the critical transition period(s) shall be a minimum of eight weeks. During the remaining period, one or more winter classes shall apply with or without VLI (Class C, C1, D, D1, E, E1, F or F1).

Of these classes, only classes C1, D1, E1 and F1 have a VLI value associated with them. Classes C, D, E and F have no vapor lock requirements. According to Ortwin Costenoble, an EU fuels expert, refiners had proposed eliminating VLI. However, internal evaluations conducted by both automakers and oil companies concluded that no change was warranted, and the consensus was to retain the VLI requirement.

Fuel Octane

The Driveability Index of a fuel is tied to the octane rating of the fuel. For example, components that tend to increase the octane number of the fuel, such as aromatics, also tend to have high boiling points that increase the DI of the fuel. The oil companies therefore face a challenge in the production of high octane premium fuel, since octane and DI are at least partially correlated.

The octane number of a fuel describes the anti-knock quality of the fuel. Knock is the term given to the pinging sound that can emanate from a SI engine at high load. The high in-

cylinder temperatures and pressures cause the air-fuel mixture at the periphery of the cylinder – termed as end gas – to autoignite ahead of the travelling flame front. The autoignition of the end gas leads to high pressure oscillations in the engine cylinder, which cause the pinging sound, and are termed as knock. At low magnitudes, knock is just an audible noise that may be interpreted as a negative issue by the driver. However, at high magnitudes, knock can cause structural damage to the engine or lead to run-away pre-ignition. Knock can be mitigated in several ways.

(i) Retarding the spark timing from the maximum brake torque (MBT) spark timing,
(ii) Enriching the air-fuel mixture
(iii) Downshifting to increase engine speed

But all these solutions come at the expense of increased fuel consumption and reduced brake thermal efficiency of the engine. In the case of fuel enrichment, there is also the issue of increased emissions. Knock mitigation without compromising on the efficiency of the engine can be achieved by using a fuel with better anti-knock quality. The higher the anti-knock quality of the fuel, the better the resistance it possesses against autoignition and closer it can be run to MBT.

The anti-knock quality of a fuel is quantified using octane numbers. The two octane numbers typically associated with gasoline are Research Octane Number (RON) and Motor Octane Number (MON). The RON for a fuel is measured using ASTM D2699 [67] and the MON is measured using ASTM D2700 [68]. The average of the two octane numbers is termed anti-knock index (AKI). The United States, Canada, and Mexico use AKI to denote the anti-knock quality of the fuel at gas stations, while Europe, Brazil, and Asia use RON.

Gasoline is composed of hydrocarbons ranging from C4 to C10, termed as gasoline range organics. Gasolines include four major types of hydrocarbons, stated below [69].

1. **Paraffins (Alkanes) – Saturated straight or branched chain hydrocarbons (only Carbon-Carbon single bonds)**
2. **Olefins (Alkenes) – Unsaturated straight or branched chain hydrocarbons with at least one Carbon-Carbon double bond**
3. **Naphthenes (Cycloalkanes) – Saturated hydrocarbons characterized by their ring structure**
4. **Aromatics – Hydrocarbons that contain at least one benzene ring**

The typical composition of automotive gasoline or motor gasoline hydrocarbons includes 29–48% alkanes, 2–5% alkenes, 3–7% cycloalkanes, 1–4% cycloalkenes, and 20–50% total aromatics [70]. The majority makeup of gasolines is alkanes (more isoalkanes, which are

branched chain alkanes) and aromatics. The general characteristics of alkanes relevant to gasoline are shown in Table 14 and those of aromatics relevant to gasoline are shown in Table 15.

Table 14: General properties of paraffins [63]

	iso-butane	iso-pentane	2, 3-di-methyl butane	2, 2, 3-tri-methyl pentane (isooctane)	2, 2, 3, 3-tetramethyl pentane	2, 2, 3, 3-tetramethyl hexane
Chemical Formula	C4H10	C5H12	C6H14	C8H18	C9H20	C10H22
Molecular Weight (kg/kmol)	58.1	72.1	86.2	114.2	128.3	142.3
Boiling Point (°C)	-11.2	28	58.1	110	140.3	159.4
Lower Heating Value (MJ/kg)	45.61	45.24	44.66	44.6	44.5	44.4
Heat of Vaporization (kJ/kg)	344	350	340	324	321	318
Vapor Pressure at 25°C (psi)	50.47	13.31	4.54	0.71	0.18	0.08
RON	102	92	-	100	-	-
MON	97.6	90.3	-	100	-	-

Table 15: General properties of aromatics [63]

	benzene	ethyl-benzene	1, 3, 5-trimethyl-benzene	methyl-benzene (toluene)	p-xylene	p-cymene
Chemical Formula	C6H6	C8H10	C9H12	C7H8	C8H10	C10H14
Molecular Weight (kg/kmol)	78.1	106.2	120.2	92.1	106.2	134.2
Boiling Point (°C)	80.2	136.2	164.7	110.7	138.3	176.9
Lower Heating Value (MJ/kg)	40.17	40.94	41.4	40.59	40.8	41.6
Heat of Vaporization (kJ/kg)	434	386	383	395	402	396
Vapor Pressure at 25°C (psi)	1.76	0.18	0.05	0.55	0.17	0.03
RON	101	107	137	120	124	124
MON	93	124	124	109	145	101

The addition of aromatics often increases the RON and MON (and thus, AKI) of gasoline, which is why premium fuels often have a higher proportion of aromatics as compared to regular fuel.

The higher boiling point aromatic compounds increase T50 and T90 of the mixture, which can increase the DI calculated using Equation 1 or Equation 2 (depending on the percentage of ethanol in the fuel blend) over the maximum permissible value. It can be balanced by increasing the percentage of lighter hydrocarbons which increase the front-end volatility and reduce T10 and T50, but that is accompanied by an increase in the vapor pressure of the fuel.

The Impact of Ethanol on Driveability and DI

Ethanol (C_2H_5OH) is the prominent oxygenate blended into gasoline in the United States and many other parts of the world. Relative to gasoline, as a pure chemical it has a low RVP, high HOV, higher octane, and approximately 33% lower energy content. The properties of gasoline and ethanol are compared in Table 16 below.

Table 16: Comparison of gasoline and ethanol fuel properties [71-73]

Property	Units	E0 Gasoline	Ethanol
Chemical Formula	-	~C8H15.6	C2H5OH
Molecular Weight	g/mol	~110	46.1
Stoichiometric AFR	-	14.2 - 15.0	9.0
Reid Vapor Pressure	kPa (psi)	56-60 (8.1-8.7)	17 (2.5)
Heat of Vaporization	Mj/kg @ 25°C	0.35	0.84
Energy Content (LHV)	MJ/kg	44.0	26.9
RON	-	91-99	109
MON	-	82-89	90
Flash Point	°C (°F)	-45 (-49)	12.7 (55)
Autoignition Temperature	°C (°F)	257 (495)	423 (793)

In the early 1990s, methyl tertiary butyl ether (MTBE) was the dominant oxygenate in gasoline. But after groundwater contamination concerns related to MTBE were discovered in the early 2000s, MTBE was promptly banned or restricted in many states [74]. To continue meeting oxygenate requirements, refiners shifted to ethanol which became the dominant oxygenate in the United States. When the United States Congress enacted the Renewable Fuel Standard (RFS) in 2005, it set a requirement for the minimum annual volume of renewable fuel in motor fuels [75]. This was most easily met by blending ethanol with gasoline. In much older cars, ethanol provided a cleaner burning, higher octane fuel that

reduced CO and HC emissions, displaced aromatics, and supported compliance with modern emissions and renewable fuel policies [76]. As shown in Figure 27, the legislation brought a rapid rise in ethanol fuel consumption and blending in gasoline. Now over 98% of gasoline sold in the United States contains ethanol [77].

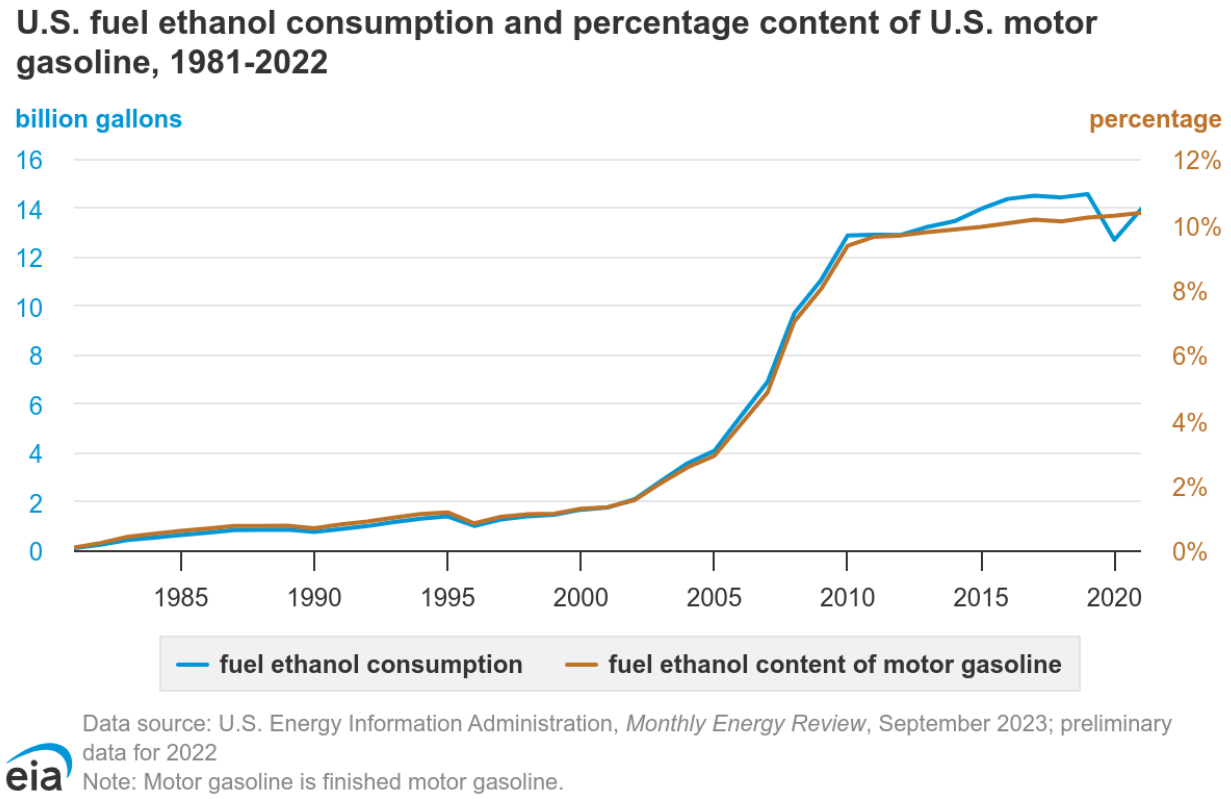


Figure 27: U.S. fuel ethanol consumption and percentage content of U.S. motor gasoline (1981-2022)

E10 is now the norm and can be found at nearly every gas station. In 2011, the EPA granted a partial waiver for the sale of ethanol-gasoline blends with up to 15% ethanol [78]. As of 2025, E15 fuel has emerged in some markets around the United States where over 4100 gas stations in 33 states sell E15 gasoline [79]. Although mid-level ethanol blends are technically feasible, ethanol use above E10 has historically been limited by a combination of vehicle-fleet considerations, retail compatibility, market factors, and fuel-property interactions, often described as the “blend wall” [80]. From a Driveability Index (DI) perspective, ethanol exhibits non-linear changes that may influence DI [76]. Table 17 summarizes the property effects of ethanol in gasoline blends, which will be discussed further in the following sections below.

Table 17: Generalized effects of ethanol on gasoline parameters

Property	Ethanol Concentration [%]		
	0 to 10	10 to 30	30 to 50
T10	↓	↓	↓
T50	↓↓↓	↓	
T90	↓	↓	↓
HOV	Linear Increase		
RVP (psi)	↑↑↑	↓	↓
TVL20 (°F)	↓ ↓ ↓	↑	↑
Octane	Non-linear increase		

The changes in volatility parameters displayed in Table 17 provide the general trends found in literature [6, 72, 76]. Exact values cannot be given due to the impact of the base hydrocarbon constituents on the magnitude of change from ethanol. Also note that the effects on the distillation curve have shown to reverse in rare cases where a very low T50 E0 fuel resulted in an increase in T50 with the addition of ethanol. Overall, ethanol addition to gasoline results in decreased T50, increased RVP up to about E5 and a gradual, but major reduction to E100 with $T_{V/L=20}$ mirroring the behavior of RVP. HOV and octane rating both increase from E0 to E100. Although these effects have been studied in detail, the difficulty in regulating volatility parameters in gasoline-ethanol blends arises from the fact that the effects are dependent on the base hydrocarbon constituents in addition to the non-linear changes in RVP, TVL20, and the distillation curve.

Although not the focus of this study, it should be noted that two additional fuel standards exist for mid-level ethanol fuel blends and E85 fuel blends. The mid-level ethanol fuel blend standard practice, ASTM D7794 covers blending of fuels with ethanol concentrations greater than conventional fuel vehicles covered in ASTM D4814 and less than Flex Fuels (E85 fuels) covered in ASTM D5798.

1) Regulation and Certification

As mentioned above, the Renewable Fuel Standard (RFS), created by Congress in 2005 and expanded in 2007 with the Energy Independence and Security Act (EISA), is what set the requirement for the use of renewable fuels in United States motor fuels. It does not set a required blend level, but a total required volume of renewables blended into gasoline per year [75]. As ethanol (and biodiesel) were the only renewable fuels with the ability to scale their volumes and meet the requirements, they were effectively mandated. The goal of this program was to reduce greenhouse gas emissions, improve U.S. energy security, and

support agriculture. The constituents and overall quality of ethanol are regulated by adopting ASTM D4806 as a legal requirement providing a consistent product to the gasoline blending industry. Ethanol makes its way into ASTM D4814 through several avenues. The standard when adopted by authorities as the legal requirement regulates the final fuel blend (ethanol + BOB) properties where the effects of ethanol on gasoline are encapsulated with a hand blended sample evaluation - representative of the intended final blend - at the refinery before shipping the E0 fuel to be blended at a terminal down the line. There are some modifications to the gasoline specifications in ethanol blended fuels where several footnotes included for Table 1 of ASTM D4814-25 contain modifications to the base fuel specifications and are listed below.

- Footnote F:
  "For gasolines that may be blended with 1 % to 15 % by volume ethanol or all other gasolines whose disposition with ethanol blending is not known, the minimum 50 % evaporated distillation temperature shall be 77 °C (170 °F) prior to blending with ethanol. For gasoline-ethanol blends that contain 1 % to 15 % volume ethanol, the minimum 50 % evaporated distillation temperature shall be 66 °C (150 °F) for volatility classes AAA through C. For Classes D and E fuels containing 1 % to 15 % by volume ethanol, the minimum 50 % evaporated distillation temperature shall be 62.8 °C (145.0 °F). For the 62.8 °C (145.0 °F) minimum 50 % evaporated distillation temperature, no allowance shall be made for the precision of the test methods."

This exception exists because adding ethanol depresses the T50 distillation temperature. These reduced T50 limits for 1–15 vol% ethanol blends reflect CRC driveability programs (CRC 584) showing that modern fuel-injected vehicles generally maintain good cold-start and warm-up performance for ethanol blends with T50 values below 150 °F, provided that overall DI and vapor pressure remain within the ASTM D4814 volatility envelope. Moreover, blending ethanol into gasoline depresses the T50 distillation temperature substantially. Therefore, a base gasoline with an already low T50 would fall well below the acceptable volatility range if ethanol were added later, leading to potential vapor lock and increase in emissions. By restricting this lower T50 allowance exclusively to fuels that will never be blended with ethanol, ASTM prevents out-of-specification downstream mixtures while still giving refiners flexibility to produce true E0 gasolines for markets and applications where ethanol is not used.

- Footnote H:
  “See 5.2.6 for Driveability Index equations for gasoline and gasoline-ethanol blends containing no more than 15 % by volume ethanol.”

This refers to the DI ethanol modifier based on the volume percentage of ethanol blended in the gasoline. This modifier was formulated through experimental driveability studies to measure the impact of ethanol contribution on TWDs. Numerous organizations studied this effect including SAE, OEMs, and the CRC. Ultimately, CRC Report 638 [9] and CRC Report 666 [10] formulated the equations we use today. Shown in the Introduction of this report, Equation 1, added in 2006, is used for 0% to 10% ethanol and Equation 2, added in 2016, for 10% to 15% ethanol.

DI for ethanol gasoline blends up to E10.

Driveability Index (°C) = 1.5×T10 + 3.0×T50 + 1.0×T90 + 1.33×(%Ethanol by volume) (1a)

Driveability Index (°F) = 1.5×T10 + 3.0×T50 + 1.0×T90 + 2.4×(%Ethanol by volume) (1b)

DI for ethanol gasoline blends from E10 to E15.

Driveability Index (°C) = 1.5×T10 + 3.0×T50 + 1.0×T90 + (1.33 + [(%Ethanol by volume-10)/5)]×(5.26-1.33))×(%Ethanol by volume) (2a)

Driveability Index (°F) = 1.5×T10 + 3.0×T50 + 1.0×T90 + (2.4 + [(%Ethanol by volume-10)/5)]×(9.49-2.4))×(%Ethanol by volume) (2b)

At first glance, the regulation of ethanol in gasoline appears to be straightforward. Ethanol quality is controlled by ASTM D4806, mixing rates and vapor pressure adjustments by the RFS, EPA and the states, and the final blended fuel by ASTM D4814. Logistics, however, provide some complications to the certification of ethanol-blended gasoline.

As shown in Figure 21, on the path from refinery to fuel pump, a BOB is manufactured at a refinery then transported through pipelines to distribution terminals. The BOB is mixed with ethanol at the terminal, along with deposit control additives (DCAs), and sometimes butane [26]. Ethanol and other constituents are mixed downstream from the refinery due to several reasons, listed below.

- Pipeline companies typically do not permit ethanol to be transported in gasoline pipelines due to the solubility of water in ethanol causing contamination and corrosion in the system. According to the American Petroleum Institute, the

chemical and physical properties of ethanol (notably its water affinity and propensity for corrosion) present serious operational challenges to existing petroleum-product pipelines, and ethanol and ethanol-blended fuels are therefore, "primarily transported by rail, truck, or barge" instead [76].

- Ethanol producers and petroleum refiners operate separate supply chains, so ethanol is typically transported independently (via rail, truck, or barge) and blended only at terminals rather than at the refinery [81].
- Input from Dr. Jim Simnick [26] indicates that ASTM D4814 DI limits are intended to apply at the fuel refinery and are not applied downstream of the refinery due to previous concerns regarding test precision and fuel variability associated with pipeline transport.
- States are responsible for adopting ASTM D4814 into law or regulation where new versions may or may not be adopted. The result is that states may apply different versions of D4814. This, coupled with some areas requiring RFG, and others not, results in blending complexity at many terminals.

The most recent footnote (footnote "I") in ASTM D4814 modified in the ASTM D4814-21c standard, states that,

"The DI specification limits are applicable at the fuel manufacturing facility and are not subject to correction for precision of the test method".

Where a fuel manufacturing facility is defined by US EPA Definitions in CFR 1090.80: "a Fuel manufacturing facility means any facility where fuel is produced, imported, or recertified." This means the fuel that leaves the refinery must meet the specifications of ASTM D4814 as a finished fuel down the line. The refinery therefore must anticipate the final blended fuel constituents (ethanol, butane, DCAs) and produce a BOB that will meet the ASTM specifications after the blending process down the line is complete. Confirmed by fuel experts from oil refineries, Dr. Jim Simnick, Russ Lewis and Matthew Sheehan all indicated the certification at the refinery is performed by hand blending a small quantity of the BOB with the intended amount of ethanol in the finished fuel.

Two situations arise from this caveat.

1. If all of the BOB is intended to be mixed with ethanol, it can leave the facility (after certification with the hand blended ethanol) with a DI above specification and a vapor pressure about 1-2 psi below specification. The mixing with ethanol downstream will decrease the calculated DI back into specification and raise the vapor pressure.

2. If a premium, ethanol-free (E0) recreational fuel (90 AKI) is to be sold during the summer, it must comply with ASTM D4814 specifications, including the summer DVPE requirement. In practice, recreational E0 is sold in relatively small volumes, typically in regions with significant motorsport, marine, or legacy-vehicle activity, making it economically impractical to produce a dedicated high-octane E0 batch. As a result, a single BOB, typically premium, PBOB, may be required to meet ASTM D4814 specifications both as a hydrocarbon-only fuel and after downstream ethanol blending. This dual requirement constrains refineries, as light-end components must be limited to achieve both high octane and summer vapor-pressure compliance; however, subsequent ethanol blending increases both octane and vapor pressure. Consequently, the E0 fuel must be manufactured with vapor pressure below the ASTM limit to accommodate the expected vapor pressure increase upon ethanol addition, effectively requiring increased light-end removal and storage for winter use.

B) Investigation of Ethanol's Impact on Gasoline and Vehicles

As summarized in the introduction of this section, ethanol has numerous impacts on gasoline volatility and ultimately affects the DI, octane, HOV, $T_{V/L=20}$, and vapor pressure of gasoline. These effects require refineries to produce a BOB that will meet ASTM D4814 specification *after* it is blended with ethanol. In short, this allows a higher DI, lower octane, and lower RVP at the refinery gates.

Unlike the addition of hydrocarbons, ethanol effects on gasoline have been found to be non-linear due to the complexity of mixing with certain hydrocarbons in gasoline [76]. The high-polarity molecules of pure ethanol can form an azeotrope like mixture with the light, low boiling point, hydrocarbons in the gasoline. This creates non-linear property effects. As ethanol contribution is increased beyond 10% v/v, heavier hydrocarbons cease to create an azeotropic mixture and the gasoline-ethanol blend increasingly has ethanol-like properties [82].

The impacts ethanol has on the properties of gasoline and the subsequent result of those effects on driveability are summarized below.

1) Gasoline Property Impacts

The fuel-property impacts of ethanol blending in gasoline have been extensively documented, with a consistent theme across the literature: ethanol produces non-linear changes in volatility including distillation behavior, vapor pressure, and vapor–liquid ratio

due to non-ideal interactions between the polar alcohol and non-polar hydrocarbons. A study conducted by the American Petroleum Institute (API) [76] blended 71 ethanol-free gasoline samples at 0, 10, 12.5, 15, 20, and 30 vol% ethanol, creating a broad fuel matrix. This enabled a systematic evaluation of how mid-level ethanol blends alter vapor pressure, distillation, vapor-liquid ratio, and octane number. The key findings are summarized below.

a Vapor Pressure:

The API study confirmed the well-known non-linear vapor pressure response to ethanol addition. Vapor pressure rises sharply up to about ~5% ethanol, then gradually declines as ethanol content increases.

- Initial Vapor Pressure Increase:
  Although pure ethanol has a low RVP (~2.3 psi), ethanol and light gasoline hydrocarbons form positive azeotropes, yielding a blended vapor pressure higher than either constituent. This effect is strongest at low ethanol concentrations, consistent with prior volatility studies [82, 83]. Because gasoline contains a wide distribution of hydrocarbons, the magnitude and shape of the RVP response vary depending on which hydrocarbons, and in what proportions, are present in the base fuel.
- Vapor Pressure Decrease Beyond ~5% Volume Ethanol:
  As the ethanol fraction increases, the lightest hydrocarbons, responsible for the azeotropic enhancement, are increasingly diluted, and the mixture's properties shift toward ethanol-like volatility. Vapor pressure therefore decreases toward the intrinsic vapor pressure of ethanol with continued ethanol addition past about 5% and to 100% by volume, as can be seen in Figure 28 [76]. This increase in vapor pressure creates a challenge for refiners to meet summer RVP limits. The EPA combatted this with a waiver allowing summer gasoline up to E10 to be sold with a 10 psi RVP, instead of at the standard 9 psi. The EPA also commonly grants an emergency fuel waiver to allow gasoline up to 15% ethanol to be sold during the summer seasons and includes the 1 psi RVP limit increase.

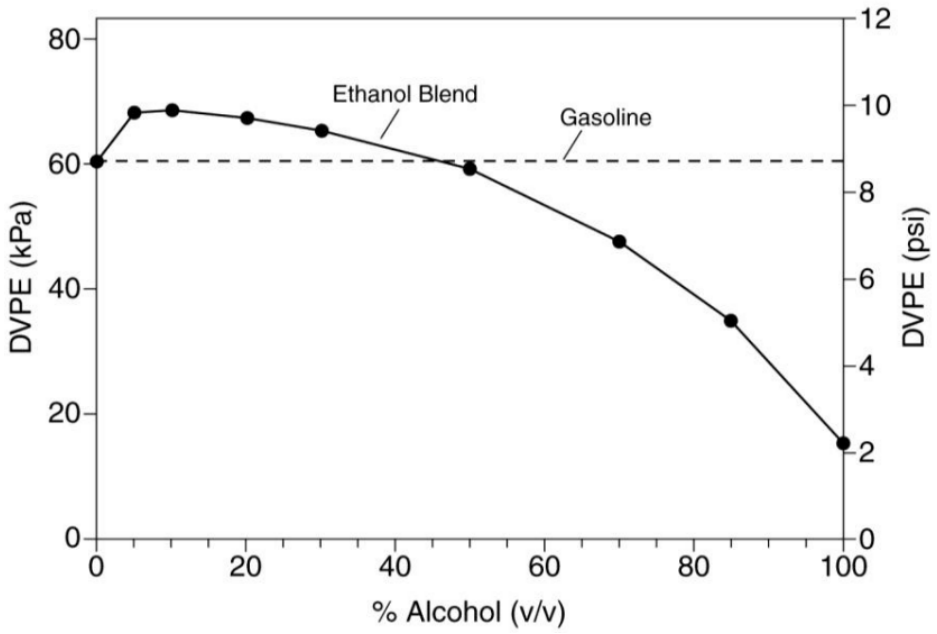


Figure 28: Effect of ethanol blending on vapor pressure of gasoline [76]

b Distillation Curve:

Ethanol–hydrocarbon interactions lower mid-range boiling temperatures, shifting T50 down, particularly with light winter fuels. The API study shows this effect creates a flattening effect of the distillation curve as ethanol contribution is increased, where the flat section is "pushed" to the right of the distillation curve beyond the 50% point. Figure 29 below from the API study shows this effect from E0 to E30. Note that the magnitude of this effect is dependent on the hydrocarbons present in the base fuel. This is consistent with other distillation curve analyses and attribute these shifts to azeotropic interactions and molecular clustering [84, 85]. Furthermore, once the azeotropic mixture is boiled off, the distillation curve quickly shifts back to its base hydrocarbon curve, creating a bump in the distillation curve.

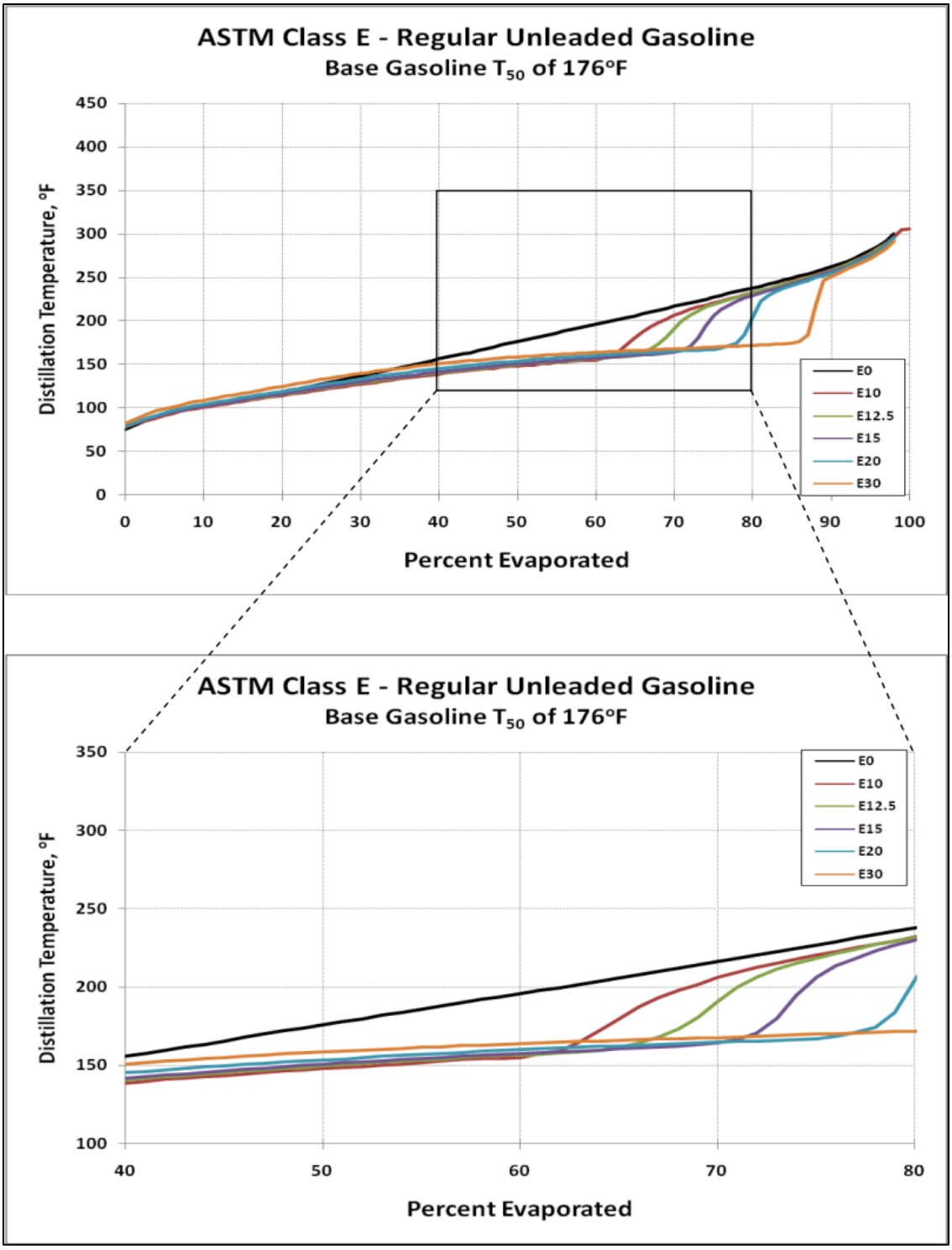


Figure 29: Effect of ethanol addition on D86 distillation temperature for a light winter retail base gasoline with low T50 [76]

The effect of different ethanol concentrations on T50 are singled out in Figure 30 and Figure 31 to further describe the dependence of the T50 decrease on the base hydrocarbon constituents.

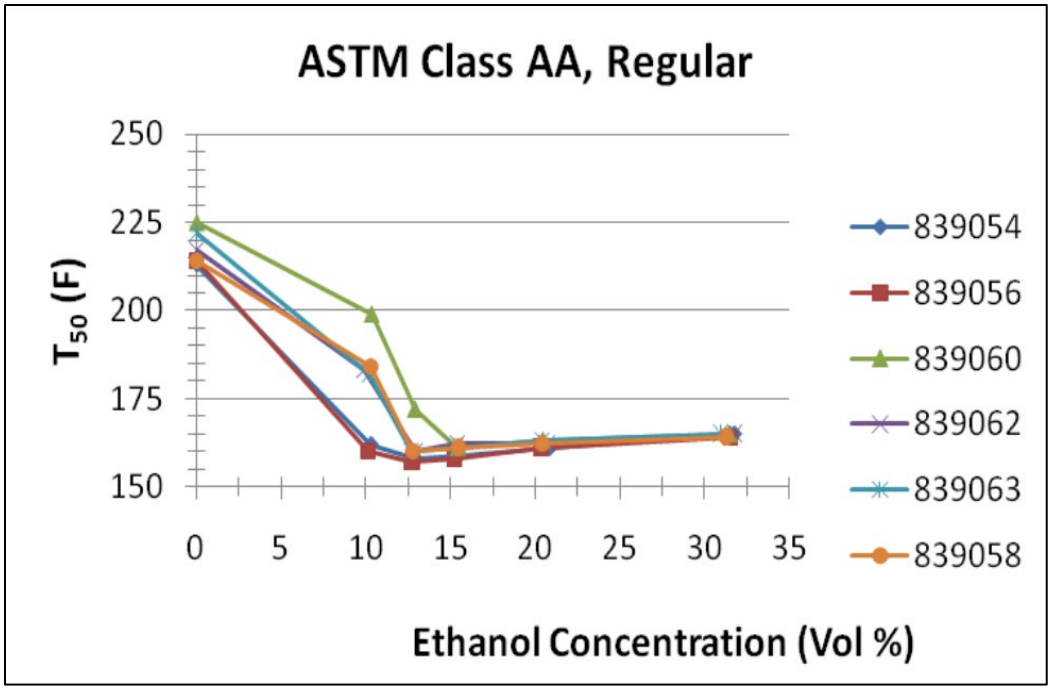


Figure 30: Effect of ethanol on T50 for multiple Class AA heavier summer gasolines [76]

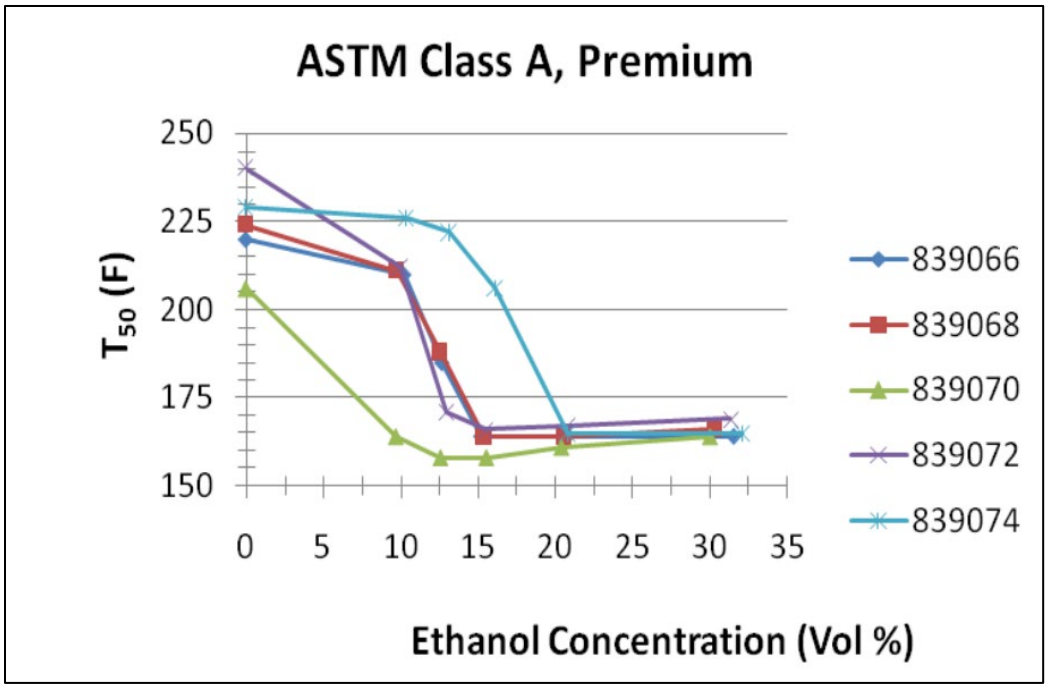


Figure 31: Effect of ethanol on T50 for multiple Class A summer gasolines [76]

Figure 30 and Figure 31 show that as ethanol is added to different base gasolines, the magnitude of T50 reduction varies from fuel to fuel with some fuels showing a profound depression in T50 and others lightly unaffected. Although the trends are generally the same, this difference in effects provides uncertainties in the DI equation, where T50 has a 3.0 multiplier.

c Vapor-Liquid Ratio ($T_{V/L=20}$):

The temperature at which the vapor-liquid ratio reaches 20:1 ($T_{V/L=20}$) was also found to respond non-linearly to ethanol addition. As ethanol lowers mid-range boiling temperatures and increases light-end volatility at low blend levels, $T_{V/L=20}$ tends to decrease up to around 10 vol% ethanol, producing mixtures that vaporize more readily under cold conditions, and flatline or slightly increase at mixtures above 10 vol% ethanol. The effect depends strongly on the hydrocarbon composition of the base gasoline, with higher isopentane or light-paraffin content amplifying the non-ideal vapor-liquid behavior [76]. Notably, this effect is essentially an inverse of the DVPE increase caused by ethanol where Yanowitz et al. [11] conducted an examination of fuel survey data showing DVPE and $T_{V/L=20}$ to be inversely correlated. In discussing vapor pressure and $T_{V/L=20}$, the study also notes that the investigation of the fuel survey showed T10 within a few degrees of $T_{V/L=20}$. This similarity, paired with the inverse correlation of vapor pressure and $T_{V/L=20}$ shows there is a possible over constraint in the fuel volatility standards, although they are regulated for separate purposes and by separate entities. The EPA regulates vapor pressure to control evaporative emissions, and ASTM regulates $T_{V/L=20}$ for hot fuel handling where removal of $T_{V/L=20}$ from ASTM D4814 could cause issues in vehicle evaporative systems.

d. Octane

Ethanol addition to gasoline causes an increase in the octane number. The magnitude of this increase depends on the base gasoline octane rating, with larger gains observed in regular-grade fuels and smaller gains in premium-grade fuels. As shown in Figure 32, octane has a fairly linear increase in the E0 to E20 range, after which the incremental benefit plateaus and in some cases, in the API study, decreased slightly, depending on the hydrocarbon composition of the base gasoline blendstock. These trends reflect ethanol's inherently high-octane rating as well as non-linear blending interactions between ethanol and specific hydrocarbon classes.

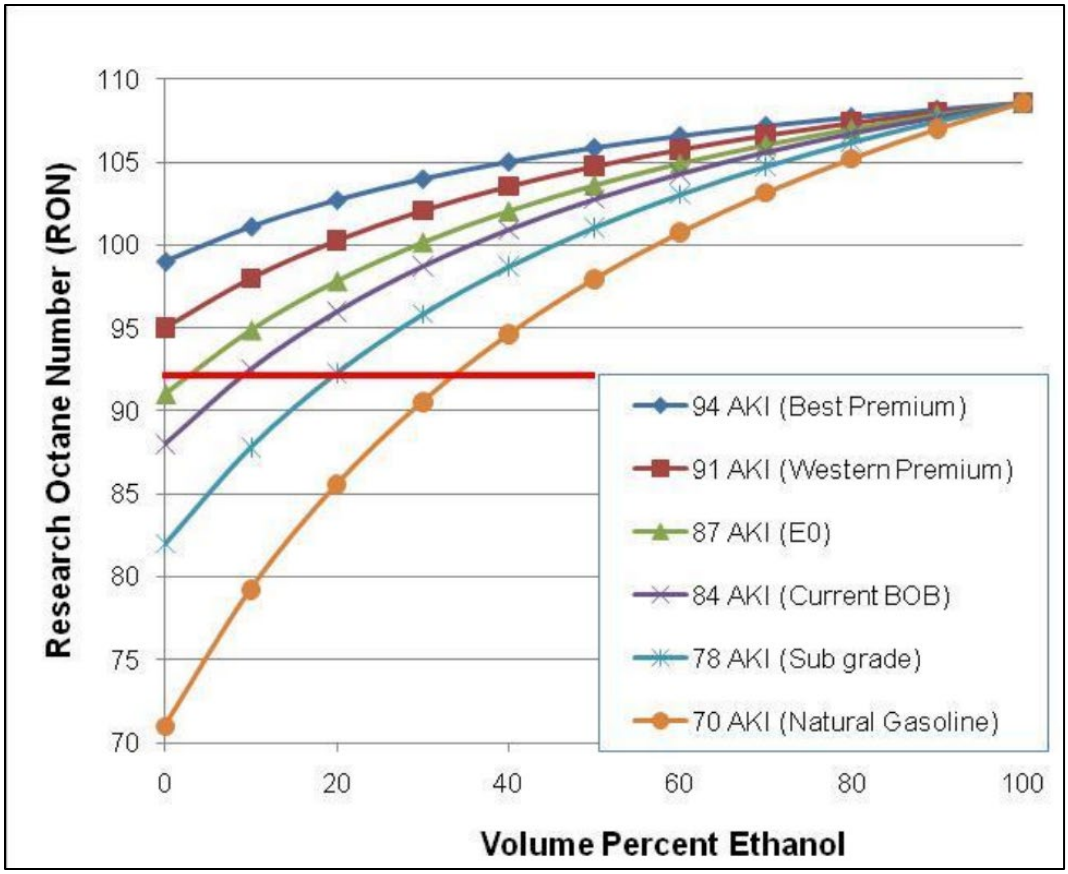


Figure 32: Octane rating vs ethanol concentration for various gasoline blends [76]

e. Heat of Vaporization (HoV):

One effect of ethanol not included in the API study is the HoV effects. Ethanol has a higher heat of vaporization than E0 gasoline, with typical values for E0 gasoline blends near 0.35 MJ/kg at 25°C and pure ethanol at 0.84 MJ/kg at 25°C [86]. This effect was studied by Chupka et al. [72] where ethanol was blended up to 50% by volume into several different gasoline blends. Researchers found that blending ethanol increases the mixture's HoV in a linear manner, as shown in Figure 33.

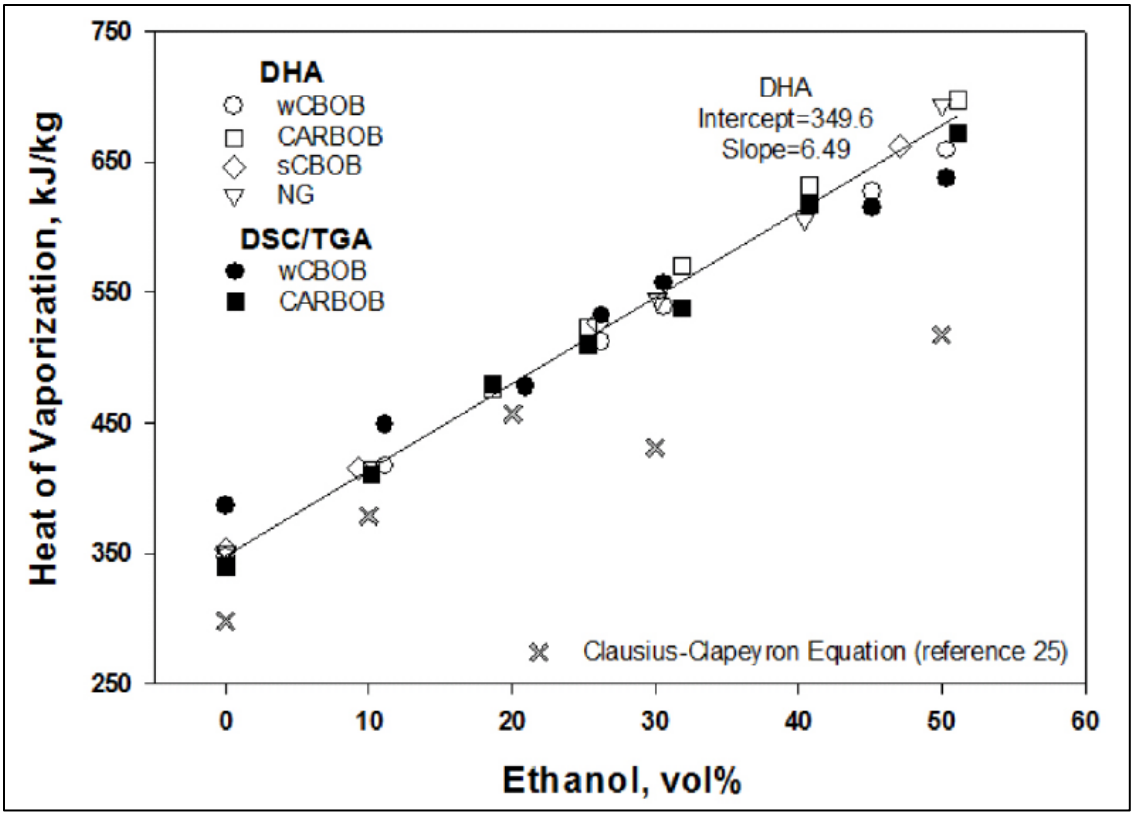


Figure 33: Ethanol concentration vs HoV for multiple gasolines [72]

Higher HoV causes mixture cooling during port or early direct injection and can impact fuel vaporization, wall wetting, and cold-start mixture preparation. These can consequently increase emissions, increase propensity for SPI, and cause driveability issues.

DHA and DSC/TGA are HOV estimation methods used to analyze the fuel in the cited project. Definitions for the legend in Figure 33 are included below.

DHA: Detailed Hydrocarbon Analysis
DSC/TGA: Differential Scanning Calorimetry/Thermogravimetric Analysis
wCBOB: Wintertime Conventional Blendstock for Oxygenate Blending
CARBOB: California Air Resources Board Reformulated Blendstock
sCBOB: Summer Class AA Blendstock from an Ozone Non-attainment Area
NG: Natural Gas

The non-linear property shifts described above complicate the efforts to regulate fuel quality as ethanol and base hydrocarbon content varies, especially as interest in E15 and higher blends grows and the non-linear regions of ethanol blended gasolines properties are penetrated. The next section examines how these effects manifest at the vehicle level and how modern fuel systems and controls have adapted to maintain driveability and emissions compliance.

f. Vehicle Impacts

- Modification of fuel systems and valve seats

The introduction of ethanol blended gasoline required OEMs to redesign fuel system components to prevent degradation of materials not compatible with ethanol (e.g., certain elastomers, polymers, and sealants). As a result, vehicles produced prior to 2001, boats, motorcycles, and lawn and garden equipment do not have a Clean Air Act waiver to legally use gasoline-ethanol blends above E10. Modern vehicles use ethanol compatible materials throughout the fuel system and are typically validated and warranted for blends up to at least E10, with many warranted for E15. Additionally, the introduction of E15 has required harder valve seats and valve seating surfaces.

- Enleanment Effect

Because ethanol is an oxygenate, its addition to gasoline lowers the stoichiometric AFR of the blend, producing an enleanment effect if fueling is not adjusted. Modern vehicles manage this through closed loop control, fuel trim adaptation, and in some cases direct ethanol content sensing. However, engines without closed-loop feedback, such as carbureted small engines, power generators, classic cars, recreational vehicles, and many marine and industrial engines, cannot compensate, leading to hot operation and loss of catalyst protection enrichment and durability concerns. For this reason, E0 is more commonly sold in regions with high boating or recreational vehicle use.

- Evaporative Emissions

Ethanol influences evaporative emissions both through its effect on volatility and through its interaction with the evaporative control system. While ethanol vapors are more effectively adsorbed by activated carbon canisters than many hydrocarbons, the non-linear changes in RVP and distillation can increase the vapor load entering the canister under certain blend conditions. These interactions require careful calibration of purge strategies and canister sizing to maintain compliance with evaporative-emissions standards, particularly as ethanol content and base-stock volatility vary across regions.

- Positive Crankcase Ventilation (PCV)

Since ethanol has a fixed boiling point (i.e. the "flat spot" in the distillation curve) it can present a challenge. Under cold conditions fuel can accumulate in the oil. As the oil warms up, the fuel boils off gradually and goes through the PCV system displacing injected fuel to maintain stoichiometry. Conversely, as the oil hits the ethanol boiling point, all the ethanol comes out quickly and can overwhelm the system.

Although modern vehicles are now far better equipped to adapt to fuel variability, ethanol's non-linear property effects still complicate fuel regulation and necessitate the continued availability of E0 for applications unable to compensate. These issues highlight why real-world performance must be assessed through driveability, which the next section explores using key DI studies.

g. Driveability Impacts

The Driveability Index (DI) was developed to ensure reliable cold-start and warm-up performance while allowing OEMs to meet emissions standards. While the current specification performs effectively in the market, the underlying DI equation was not originally designed for ethanol, and the ethanol correction factors currently in use were developed from relatively small fuel datasets using vehicles calibrated to now outdated emissions standards and fuel systems that have undergone significant improvements. As ethanol continues to be used in the market as E10, further penetration is made by E15, and possible higher content, mid-level blends, there is reason to conduct research to further understand whether the DI framework is still relevant in modern vehicles and if the ethanol modifications to the standard need to be reworked or modernized. This section summarizes the major studies that established ethanol-related driveability correlations and highlights the limitations of those studies relative to today's vehicles.

2004 CRC Cold-Start and Warm-Up Driveability Study (E0–E10)

Details from this study are covered in the History of DI section of the report and can be referred to for further details. In this analysis on the effects on driveability, the findings can be summarized into two key takeaways:

1. The addition of ethanol to a base hydrocarbon fuel reduced the TWD at 3%, 6% and 10% ethanol addition by volume

This shows that the decrease in T50 from ethanol addition is sufficient to overcome the impact of increased HoV, or increased charge cooling, as well as the enleanment effect.

2. An ethanol fuel with a matching volatility to an E0 fuel results in increased TWD

The increased demerits measured with the volatility matched ethanol blends, and the known effects of ethanol on a hydrocarbon fuel, tells us that the base hydrocarbon used to produce

a blend with an equivalent volatility had a DI significantly higher than 1300. The ethanol addition to these high DI base fuels, would likely have produced a decrease in TWD when compared to their base fuels, if tested.

Overall, ethanol showed a decrease in TWDs in comparison to the base fuel, but its effects did not align with the original DI equation, leading to the development of the first ethanol correction term for ethanol-blended fuels up to E10. The fuel matrix was relatively small, compared to the research conducted in the creation of the DI and used vehicles with early closed-loop fueling strategies, so its findings are not fully representative of what might be found in modern engines.

2014 CRC Report No. 666 – E15 Driveability Evaluation

CRC Report 666, is also summarized in the History of DI section of this report. The findings from this project differ slightly from those of the CRC-638 findings:

- Ethanol addition showed no significant change in TWD

The small changes measured in TWD are contrary to the TWD effects of ethanol in CRC-638. This difference in results displays the dependence of the ethanol's fuel volatility effects on the base hydrocarbon constituents and therefore the TWDs.

- GDI engines received higher demerits than PFI engines.

This finding initially suggests that GDI engines are less robust to driveability issues. However, at this point in time, as shown in Figure 13, GDI was a relatively new technology where significant advances in the technology have been made since 2013.

2020 CRC/FEV Ethanol Driveability Program

The 2020 CRC/FEV program focused on determining whether coefficient of variation (COV) of IMEP could serve as a surrogate for driveability. It did not measure driveability demerits and did not generate updated DI correlations. Several of the tested vehicles were not calibrated or warranted for mid-level ethanol blends, and the study's results are difficult to apply directly to DI development. The program demonstrated that modern GDI engines are generally tolerant of ethanol up to E15 under controlled volatility, but it did not address how ethanol affects real-world cold-start driveability.

Other Relevant SAE Driveability Studies

SAE literature shows that ethanol influences driveability through a combination of effects: improved mid-range volatility, increased enleanment, higher heat of vaporization, and changes in vapor-liquid behavior. Modern vehicles typically mitigate these effects through advanced fuel control and cold-start strategies, but sensitivity to ambient temperature and

volatility still exists. Studies consistently show that ethanol-related driveability effects are vehicle-specific and strongly dependent on the base fuel.

Observations and Knowledge Gaps

Across all major studies, several consistent themes emerge:

1. Ethanol influences driveability through multiple competing mechanisms.
2. The DI ethanol modifiers were derived from smaller datasets than the original DI equation studies.
3. No study has evaluated DI or ethanol modifiers using current-generation GDI engines or emissions-driven cold-start strategies.
4. Conflicting results between CRC-638 and CRC-666 suggest either that ethanol blended fuel's impact on driveability is not only influenced by the ethanol volume, but also by the constituents of the base hydrocarbon, or the advancement in technology and calibrations in the time between the two studies, changed how vehicles react to ethanol blended fuels.
5. The base DI equation does not capture ethanol's nonlinear fuel-property effects.
6. None of the studies included an assessment of emissions, where poor driveability would result in increased emissions.

These gaps suggest that while DI and its ethanol modifiers are functional today, the system has not been validated in modern vehicles.

Summary

Ethanol is an oxygenated blending component added to gasoline primarily for octane enhancement, renewable-fuel compliance, and emissions benefits and to increase the overall volume of SI fuel available to the market. Its use in the United States is governed through volumetric renewable-fuel requirements, blend limits (such as E10 and E15), and the fuel-quality specifications of ASTM D4814.

Ethanol affects gasoline properties in several important ways. It modifies volatility and distillation behavior in distinctly non-linear patterns due to azeotropic interactions and vapor–liquid non-ideality; increases HoV; and raises the octane rating. These effects depend strongly on the composition of the base gasoline and become more pronounced as ethanol concentration increases.

Driveability studies show that ethanol can influence cold-start and warm-up performance through competing mechanisms: improved volatility (lower T50), higher enleanment

tendency, increased charge cooling due to a higher HoV, and changes in vapor pressure and $T_{V/L=20}$. Across the CRC and SAE literature, E10 and E15 fuels generally perform acceptably when volatility is controlled, but the DI equation requires ethanol-specific modifiers to maintain correlation with observed driveability. These modifiers were derived from relatively small fuel (in comparison to market fuel spread) datasets and reflect vehicle technologies that are no longer representative of the modern fleet, as outlined in the Vehicle Technology Section of this report.

A clear gap now exists in understanding how ethanol affects driveability in modern vehicles. Since the foundational studies were conducted, vehicles have undergone significant changes: widespread adoption of direct injection, more capable closed-loop fuel control, enhanced evaporative-emission systems, and cold-start calibrations designed for increasingly stringent emissions standards. The non-linear effects of ethanol on fuel properties and the knowledge that those effects are dependent on the base hydrocarbon fuel paired with the conflicting results of CRC-666 and CRC-638, suggest that the correlations found in the previous studies may not fully represent ethanol's impact on driveability. Collectively, these developments raise the question of whether the DI framework, its ethanol modifiers, or its underlying distillation points could be refined or simplified while still ensuring robust vehicle performance and enabling practical, consistent fuel production.

Determining this requires experimental work to evaluate ethanol's effects on driveability using modern vehicle technologies, current emissions requirements, and representative blendstock formulations. These studies will form the basis of a recommendation in the next section.

Additional Considerations – Fuel Volatility Influence on Stochastic Pre-ignition (SPI) and Particulate Mass/Particle Number (PM/PN) Emissions

The focus of this project has been on the relationship between fuel volatility and cold start and warm-up driveability, and whether DI is still relevant in modern vehicles. As has been shown elsewhere in this report, cold start and warm-up driveability are influenced most strongly by the low and mid-range portions of the distillation curve (IBP, T10, T50, T70, DVPE, etc.), while T90 is one of the distillation metrics included in the current DI calculation. It has been suggested that DI may be better represented - and more closely tied to driveability issues - by focusing on distillation temperatures lower in the curve (i.e. T70 and below) [38].

This raises the question of the importance of T90 and FBP – and potentially even T70 - for engine and vehicle cold start and warm-up performance. But there is substantial literature supporting its influence on stochastic or low-speed pre-ignition (SPI or LSPI) and particulate matter / particulate number emissions (PM/PN). An indirect impact of the current DI equation is that it helps to keep the T90 value of the fuel well below the ASTM D4814 limit, especially in the summer, when a lower RVP limit is in place.

Previous studies have shown correlation between SPI rates and the upper end of the fuel volatility curve. Figure 34, generated by Chapman et al. [87], for example, shows a strong correlation between SPI rate and T70. A study by Southwest Research Institute, General Motors, and Aramco Research Center [88], concluded that "Aromatic content and heavy-end distillation, either separately or expressed as the particulate matter index (PMI) number, are consistently the best indicators of the SPI frequency and severity."

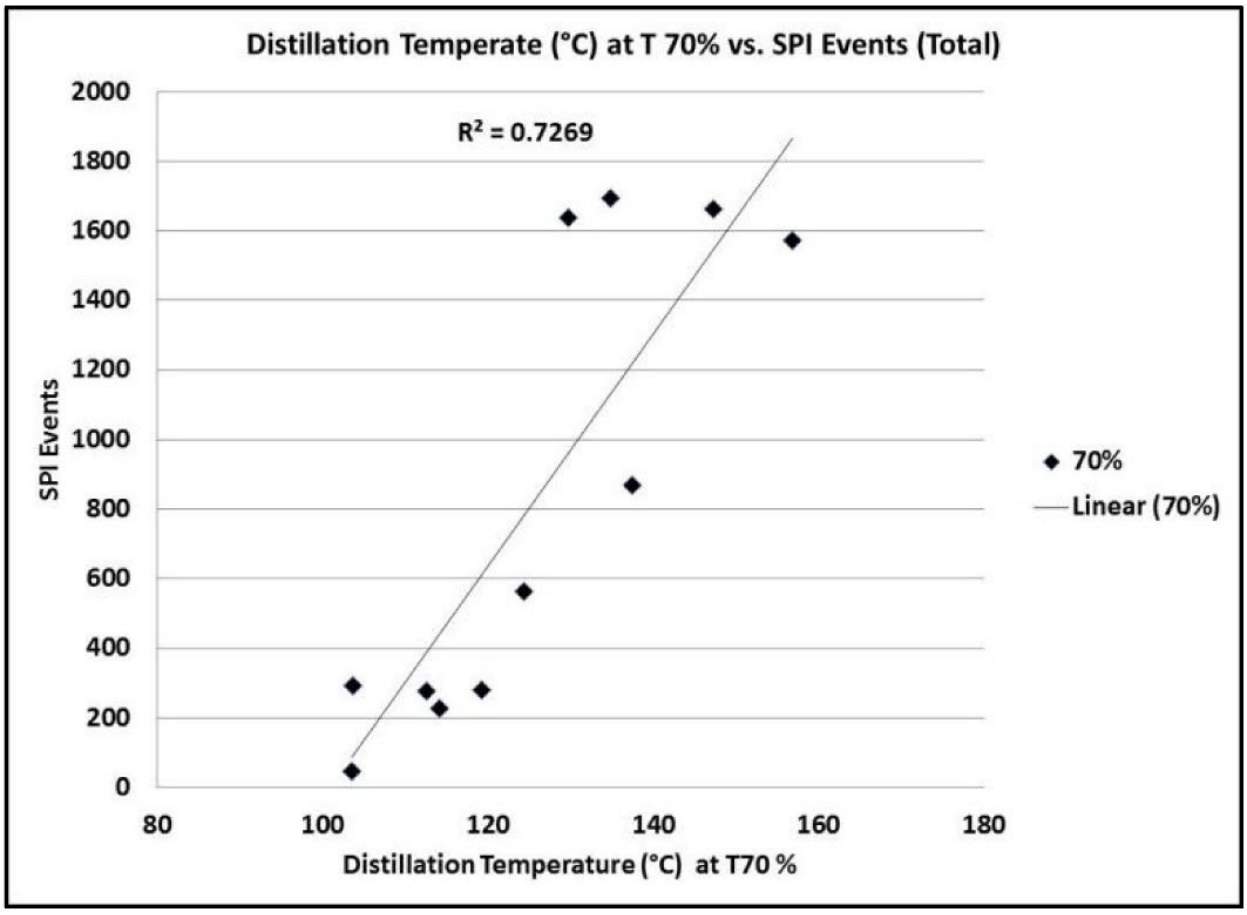


Figure 34: SPI events versus T70 distillation temperature [87]

Many studies have linked fuel volatility parameters – along with the chemical composition of the fuel – to particulate matter emissions. A 2022 journal article from the SAE International Journal of Fuels and Lubricants reviewed several particulate matter indices [89]. Many of

these indices include terms covering the higher end of the distillation curve such as T70, and E130°C (E266°F), E150°C (E302°F) or E170°C (E338°F).

For both SPI and PM/PN emissions, the primary influence of the heavier, less volatile fuel components is the tendency to form liquid fuel films on the surfaces of the combustion system or have unevaporated liquid fuel droplets persist through the combustion process. This liquid fuel is then subject to the formation of rich, post-combustion diffusion flames which generate high amounts of soot. These directly generate PM/PN emissions and can become precursors to SPI events.

Ultimately, removal of T90 from the DI calculation may require assessment of whether tighter (lower) limits for T90 and FBP are required. Alternatively, additional metrics like particulate emissions index (PEI) or PMI could be introduced to protect against fuels contributing to higher particulate emissions or higher SPI sensitivity. Dr. Pat Geng, fuels expert at General Motors, commented that "T90 is still important. On the T90 side - or anything beyond T50s - it's kind of shifting from the volatility side or from the driveability side to particulate emissions" [38].

Comparison of Gasoline Volatility Specifications from the Major Global Automotive Markets

Driveability Index (DI) is a parameter unique to a few countries, including the United States of America, as a part of the volatility specifications in the ASTM D4814 standard. Other than the US, the DI specification is used by countries that have fully adopted the standard, like Canada. For ensuring gasoline has the appropriate volatility, the ASTM D4814 regulates the following.

- **Distillation temperatures (T10, T50 and T90)**
- **Driveability Index (DI = 1.5×T10 + 3.0×T50 + 1.0xT90 + Ethanol Offset)**
- **Dry Vapor Pressure Equivalent (DVPE)**
- **Vapor lock protection classes or $T_{V/L=20}$ – The vapor-to-liquid ratio temperature for a 20:1 volume ratio**

The ASTM specifications are adopted by US states on a case-by-case basis. The volatility specifications in ASTM D4814 are shown in previous sections in Table 8. The EPA regulates summertime vapor pressure, while ASTM specifications have limits on the DVPE throughout the year.

This section aims to study the volatility regulations for other major automotive markets and compare them to the US regulations. This comparison is aimed at evaluating whether the US volatility regulations are more restrictive or complex, and if there are other viable solutions that would accomplish what the US regulations cover. Other than the United States, the volatility specifications for the following three other regions were studied in detail.

- **European Union (EU)**
- **Japan**
- **China**

Along with the United States, the three regions mentioned above are currently the biggest automotive markets globally, which is why they were chosen for the comparative analysis. The United States, Germany (which is a part of the EU), Japan and China are four of the top five countries with the highest car sales in the last three years [90-92] (India is the fifth).

Brazil ranks just outside the top five and is the country that uses the highest amount of ethanol in their gasoline fuel. Recently, the regular ethanol-gasoline blend in Brazil was revised from E27 to E30. However, as the majority of gasoline sold in the United States is E10, Brazil was not included in this comparison of volatility specifications. If the RFG requirements mandated the use of ethanol-gasoline blends over E15, the specifications used by Brazil can be compared.

European Union (EU)

Europe has a common fuel volatility standard, EN228 [93], for all countries that are a part of the EU. Unlike the United States, Japan and China, the EN228 standard does not use distillation temperatures as the applicable limits. Instead, EU specifies volatility in the Exx form, where the regulated entity is the percentage of fuel that has evaporated at xx °C. The EU permits the sale of gasoline with up to 10% ethanol by volume. The EN228 standard has two volatility class tables – one for gasoline (or petrol, as it is known there) with a maximum oxygen content of 2.7% by mass (maximum 5% ethanol by volume), and the other for a maximum oxygen content of 3.7% by mass (maximum 10% ethanol by volume). The relevant properties of the two tables have been combined below in Table 18. The EU also permits the use of other oxygenates like methanol, iso-propyl alcohol, iso-butyl alcohol, tertiary-butyl alcohol, and ethers.

In Table 18, the cells marked 'yellow' contain two values – the first applies to gasolines up to E5 (2.7% oxygen by weight) and the second applies to gasolines up to E10 (3.7% oxygen by weight) are shown in Table 18.

Table 18: Volatility classes and requirements for gasoline in the EU[8][93]

Property	Units	Limits					
		Class A	Class B	Class C/C1	Class D/D1	Class E/E1	Class F/F1
Vapor Pressure (VP)[9]	kPa, min	45	45	50	60	65	70
	kPa, max	60	70	80	90	95	100
% evaporated at 70°C (158°F), E70 (E158)	*% (V/V), min.*	20	20	22	22	22	22
	% (V/V), max.	48/50	48/50	50/52	50/52	50/52	50/52
%evaporated at 100°C (212°F), E100 (E212)	*% (V/V), min.*	46	46	46	46	46	46
	% (V/V), max.	71/72	71/72	71/72	71/72	71/72	71/72
% evaporated at 150°C (302°F), E150 (E302)	*% (V/V), min.*	75	75	75	75	75	75
Final Boiling Point (FBP)	°C (°F), max.	210 (410)	210 (410)	210 (410)	210 (410)	210 (410)	210 (410)
Vapor Lock Index (VLI) (10×VP + E70)	index, max.	-	-	C -	D -	E -	F -
Vapor Lock Index (VLI) (10×VP + E70)	index, max.	-	-	C1 1050/1064	D1 1150/1164	E1 1200/1214	F1 1250/1264

[8] The yellow cells indicate values that differ for the 2.7% and 3.7% oxygen content by mass. All other values are the same.

[9] The vapor pressure used in the EU specifications is Dry Vapor Pressure Equivalent (DVPE), which is the same vapor pressure used in ASTM D4814.

These fuel properties are adopted throughout the EU. Countries can decide on the class of gasoline based on the climate. Like the United States, ethanol-gasoline blends are permitted a vapor pressure waiver. The value of the waiver depends on the ethanol content by volume. The exact values are included in the Appendix.

The following is an excerpt from the EN228 standard[10]:

To meet hot and cold vehicle driveability requirements under the European seasonal and geographical conditions, ten volatility classes. Each country shall, in a National Annex to this document, specify for each type of unleaded petrol which of these ten volatility classes apply during which period of the year for defined regions of the country.

Class A shall apply during summer, starting no later than 1 May and ending not before 30 September. In countries with low ambient summer temperatures, Class B shall apply during summer, starting no later than 1 June and ending not before 31 August.

Each country shall apply one or more volatility classes (Class C1, D1, E1, or F1) with vapor lock index (VLI) for the transition periods on either side of summer. Each transition period shall be a minimum of four weeks. When transition periods are deemed critical, the critical transition period(s) shall be a minimum of eight weeks. During the remaining period, one or more winter classes shall apply with or without VLI (Class C, C1, D, D1, E, E1, F or F1).

The application of the vapor pressure waiver permitted for unleaded petrol containing bioethanol is restricted to countries having fulfilled the requirements.

It is interesting to note that the major difference in classes for the European volatility specifications is in the vapor pressure and Vapor Lock Index (VLI) values. The EPA regulates summer vapor pressure in the United States. The restriction of Class A and Class B gasolines in EN228 to the summer months aims to accomplish a similar goal.

The parameters that are analogous to the distillation temperatures in the ASTM D4814 specification – E70 (E158), E100 (E212) and E150 (E302) – do not change significantly based either on the class of gasoline or the percentage of oxygenates in the fuel. Based on whether the fuel is E5 or E10, there is a modest change in the E70 maximum and E100 maximum, which denote the highest percentage of fuel that can be vaporized at that temperature. An increase in ethanol from 5% by volume to 10% by volume warrants a 2% increase in the maximum evaporated fuel at 70°C and 1% increase in the maximum evaporated fuel at 100°C. Notice that the minimum percentage evaporated is 20%. There is no parameter

[10] The words from EN228 are used verbatim, except for names of test procedures to calculate parameters.

analogous to T10 in the EU fuel specifications. Front end fuel volatility is predominantly controlled through the DVPE and E70 minimum.

Since the EU specifications do not have limits on distillation temperatures, a theoretical maximum DI value cannot be calculated for the summer and winter blends based on the EN228 specification. However, the DI of fuel samples from the EU was calculated using distillation data of regular fuels samples obtained from SGS INSPIRE [12]. Table 19 shows the average DI and the standard deviation of 10th percentile fuel, 50th percentile (median) fuel, and 90th percentile fuel for summer and winter from 2020 to 2024 (five years). The 90th percentile DI for summer and winter fuels is well below the ASTM D4814 requirements (DI=1200°F for winter grade E gasoline and DI=1250°F for winter grade A gasoline). The low standard deviation suggests the repeatability of the volatility specifications from year to year. It should be noted that neither the EU nor Japan or China use Driveability Index (DI) as a parameter to regulate gasoline volatility. In this section, the DI values for gasoline sample data from these three regions have been calculated for the theoretical purposes of comparison of the gasoline samples with US gasoline samples.

Table 19: Driveability Index values calculated for gasoline samples from the EU (2020 – 2024) [12]

Season	Summer (EU)			Winter (EU)		
Fuel	10th percentile	50th percentile	90th percentile	10th percentile	50th percentile	90th percentile
Average DI (°F)	1038.6	1088.8	1154.6	992.4	1040.8	1124.8
Standard Deviation (°F)	4.9	5.6	6.9	5.0	10.3	7.9

Japan

The volatility requirements for gasoline sold in Japan are based on the JIS K 2022:2023 standard [94]. The prominent volatility specifications mentioned in the standard are shown in Table 20. Like the United States, Japan uses T10, T50 and T90 to regulate gasoline volatility along with vapor pressure. For regular gasoline (RON 89), there are two classes in the volatility standards

- First is for oxygen content by mass up to 1.3% (maximum 3% ethanol by volume)
- Second is for oxygen content by mass more than 1.3% up to 3.7% (maximum 10% ethanol by volume)

Irrespective of the class of gasoline in Japan, the distillation temperature maximum values for T10, T50 and T90 are the same throughout the year. Similar to the ASTM D4814 standard, T50 has a minimum limit, which is lower for ethanol-gasoline blends higher than E3.

The vapor pressure is regulated based on the climate, with maximum DVPE for summer at 9.4 psi and for winter at 13.4 psi. Unlike the United States, there is a minimum DVPE requirement of 6.4 psi, which is increased to 8 psi in the winter and 8.7 psi for regions with temperatures below -10°C (14°F).

Table 20: Volatility classes and requirements for gasoline in Japan [94]

Test item	Class	
	Regular	Regular (E)
10% distillation temperature (T10) °C (°F)	70 (158) max.	
50% distillation temperature T50 °C (°F)	70 (158) or over up to and incl. 105 (221)	70 (158) or over up to and incl. 105 (221) [a)]
90% distillation temperature T90 °C (°F)	180 (356) max.	
End point °C (°F)	220 (428)	
Vapor Pressure (37.8°C) kPa (psi)	44 (6.4) or over and up to and incl. 78 (11.3) [b)]	44 (6.4) or over and up to and incl. 78 (11.3) [b), c)]
MTBE volume fraction %	7 max.	
Ethanol volume fraction %	3 max.	10 max.
Oxygen content mass fraction %	1.3 or under	Over 1.3 up to and incl. 3.7
Nota [a)] The lower limit of the 50% distillation temperature shall be 65°C (149°F) when the ethanol content is more than 3% in volume fraction and when the fuel is intended for cold weather and 65 kPa (9.4 psi) for summer application. Note [b)] The upper limit of vapor pressure shall be 93 kPa (13.4 psi) when the fuel is intended for cold weather and 65 kPa (9.4 psi) for summer application. Note [c)] The lower limit of the vapor pressure shall be 55 kPa (8 psi) when the ethanol content is more than 3% in volume fraction and the fuel is intended for winter weather. Also, the lower limit of the vapor pressure shall be 60 kPa (8.7 psi) when the ethanol content is more than 3% in volume fraction and the fuel is intended for the regions where the ambient temperature can be -10°C (14°F) or lower.		

Based on the maximum permissible distillation temperature values specified in JIS K 2022:2023, the theoretical maximum DI of the gasoline will be 1256°F. This is higher than the highest DI limit specified in ASTM D4814, which is 1250°F for grade A summer gasoline (calculated using Equation 1). However, this does not reflect the reality at the pumps. Looking at average regular gasoline sample data from Japan (89 RON E0) from the 2020 to 2024 [12], the calculated DI values for the summer as well as the winter are significantly lower than the maximum DI limits of the ASTM D4814 standard. The DI values calculated for gasoline samples from Japan are shown in Table 21.

Table 21: Driveability Index values calculated for gasoline samples from Japan (2020 – 2024) [12]

Season	Summer (Japan)			Winter (Japan)		
Fuel	10th percentile	50th percentile	90th percentile	10th percentile	50th percentile	90th percentile
Average DI (°F)	1036.6	1068.8	1104.4	979.4	1021.8	1054.6
Standard Deviation (°F)	8.6	10.4	12.7	36.2	12.2	6.9

It should be noted that even though the maximum permissible ethanol percentage by volume is 10% for ethanol-gasoline blends in Japan, the prominent oxygenate used in Japan in ethyl tertiary butyl ether (ETBE). Hence, the samples used for calculating DI are E0 in terms of ethanol.

China

Volatility specifications for motor gasoline in the People's Republic of China are regulated based on the GB 17930-2016 specification [95]. Like Japan, the majority of gasoline sold in China is E0. The national average annual blend rate from 2012 to 2021 ranged between 1.8% and 2.5% [96]. The samples for motor gasoline from China obtained from SGS INSPIRE are E0. China has a single class of E0 gasoline, the relevant volatility properties for which are shown below in Table 22.

While China does use T10, T50 and T90 to regulate gasoline volatility, the entire country uses the same class with one set of distillation temperature maximums. The regulations are even less stringent than gasoline in Japan, considering T50 does not have a minimum to abide by (and significantly less stringent that the United States, where there are six different volatility classes).

The parameter controlled based on the seasons and the regional climate is vapor pressure, which has a maximum permissible value of 9.4 psi for the summer months and 12.3 psi for the winter months. Unlike ASTM D4814, vapor pressure has a minimum required value as well.

Table 22: Volatility requirements for gasoline in China [95]

Item	Value
10% evaporation temperature (T10) /°C (°F): not more than	70 (158)
50% evaporation temperature (T50) /°C (°F): not more than	120 (248)
90% evaporation temperature (T90) /°C (°F): not more than	190 (374)
Final distillation points/°C (°F): not more than	205 (402)
Vapor pressure/kPa (psi): November 1 ~ April 30 May 1 ~ October 31	 45 (6.5) ~ 80 (12.3) 40 (5.8) ~ 65 (9.4) [c]
Oxygen content (mass fraction)/%: not more than	2.7
Methanol content (mass fraction)/%: not more than	0.3
[c] In Guangdong and Hainan, this requirement shall be followed throughout the year.	

The theoretical maximum DI value based on the GB 17930-2016 is 1355°F (calculated using Equation 1), which is 105° higher than the United States maximum DI and 155°F higher than the United States minimum DI. However, similar to what is observed for the Japanese gasoline data, the calculated DI values of gasoline samples from 2020 to 2024 is well within the DI limits for the United States, even when the 90th percentile value is considered. The DI values calculated for gasoline samples from China are shown in Table 23.

Table 23: Driveability Index values calculated for gasoline samples from China (2020 – 2024) [12]

Season	Summer (China)			Winter (China)		
Fuel	10th percentile	50th percentile	90th percentile	10th percentile	50th percentile	90th percentile
Average DI (°F)	1072.6	1139.8	1185.4	1057.8	1115.8	1168.2
Standard Deviation (°F)	11.7	9.2	12.3	26.0	13.3	7.9

Comparison of Gasolines Volatility Properties Across Regions

Driveability Index Distribution from Summer and Winter 2024

Figure 35 shows the boxplot of DI values for gasoline samples from the United States, the EU, Japan and China for summer and winter gasoline blends[11]. Although DI is not a regulated parameter in the EU, Japan and China, the DI values were calculated based on the distillation temperatures and ethanol content for the purposes of comparison. The values shown on the plot are as follows:

- Upper bound of the box – 90th percentile DI value
- Lower bound of the box – 10th percentile DI value
- Horizontal line within the box – 50th percentile (median) DI value
- Cross (x) marker – Average DI value
- Error bars – Highest and lowest DI values

The samples from the United States are E10, those from the European Union are a range from E0 to E10, while the samples from Japan and China are E0.

The key takeaways from the 2024 gasoline data are summarized below.

- The major takeaway from this data is that the ASTM D4814 Driveability Index requirements are met by all countries based on the samples collected by SGS. It should be noted that DI only applies to the United States, and the calculation of DI for the other three regions is for the purposes of comparison.
    - All summer gasolines (including the maximum DI) are within 1250°F and all winter gasolines are within 1200°F.
- In all regions except China, the 10th percentile, 50th percentile (median) and 90th percentile DI values for summer gasoline are higher than the median DI for winter gasoline.
    - This difference is a requirement based on the United States ASTM D4814 specification and to a small extent the volatility classes in the EU EN228 specification. Although there is no requirement in Japan and China, the winter gasolines have a lower DI.
- China has the highest average and median DI for summer as well as winter gasoline.
- Japan has the lowest average DI for summer as well as winter gasoline.

[11] All statistical analysis is based on samples collected from each country. United States – 126 samples, European Union – 2035 samples, Japan – 115 samples, China – 272 samples. The high variability in the EU data is possibly due to gasoline samples being collected from multiple countries, ranging from E0 to E10.

- Japan and China are E0 gasolines. China having a high average DI is understandable, since ethanol suppresses T50 and reduces DI, which is the case for the US and the EU data. Japan having the lowest average DI values could be due to ETBE, since there is no ethanol to aid in the reduction of T50 and DI, although that is just a speculation. The DI equation has an offset factor for ethanol, but not one for ETBE.

The United States has the lowest median DI for winter gasolines. This could be due to the fact that refineries in the United States have to store light hydrocarbons such as butane in the summer, and end up using the stored light hydrocarbons in the winter. The maximum winter vapor pressure limit in the US is higher than all the other countries (16 psi in the US as compared to 14.5 psi, 11.3 psi and 12.3 psi in the EU, Japan and China respectively), which enables the oil companies to mix a higher proportion of volatile light components [26, 64, 65].

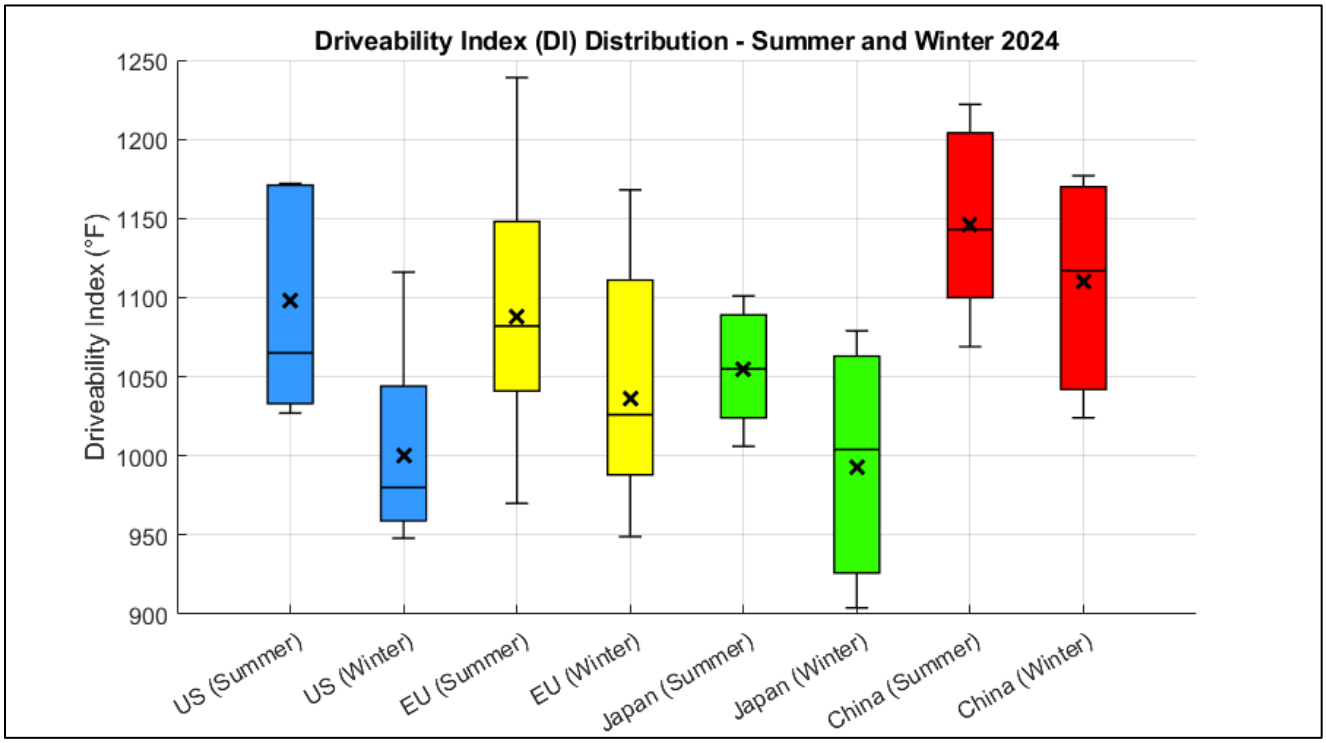


Figure 35: Distribution of Driveability Index values for summer and winter 2024 gasoline samples

Driveability Index Average Values over 5 Years

Figure 36 shows the 5-year average and standard deviation of the 10th, 50th (median) and 90th percentile DI values for the four countries for summer (top) and winter (bottom).

- The 5-year average reiterates the fact that China, for the past half decade, has had the highest DI fuel for hot and cold weather periods.
- The 90th percentile DI for winter gasoline in the US is below the median DI gasoline in the EU and China. This points back to the addition of lights and the higher vapor pressure permitted.
- The 90th percentile median DI summer gasoline in the US is higher than its EU and Japanese counterparts. The maximum vapor pressure requirement for reformulated gasoline (RFG) in the US is 7.4 psi. The high spread in DI values in the US gasoline data is possibly due to RFG samples driving the 90th percentile DI values high.

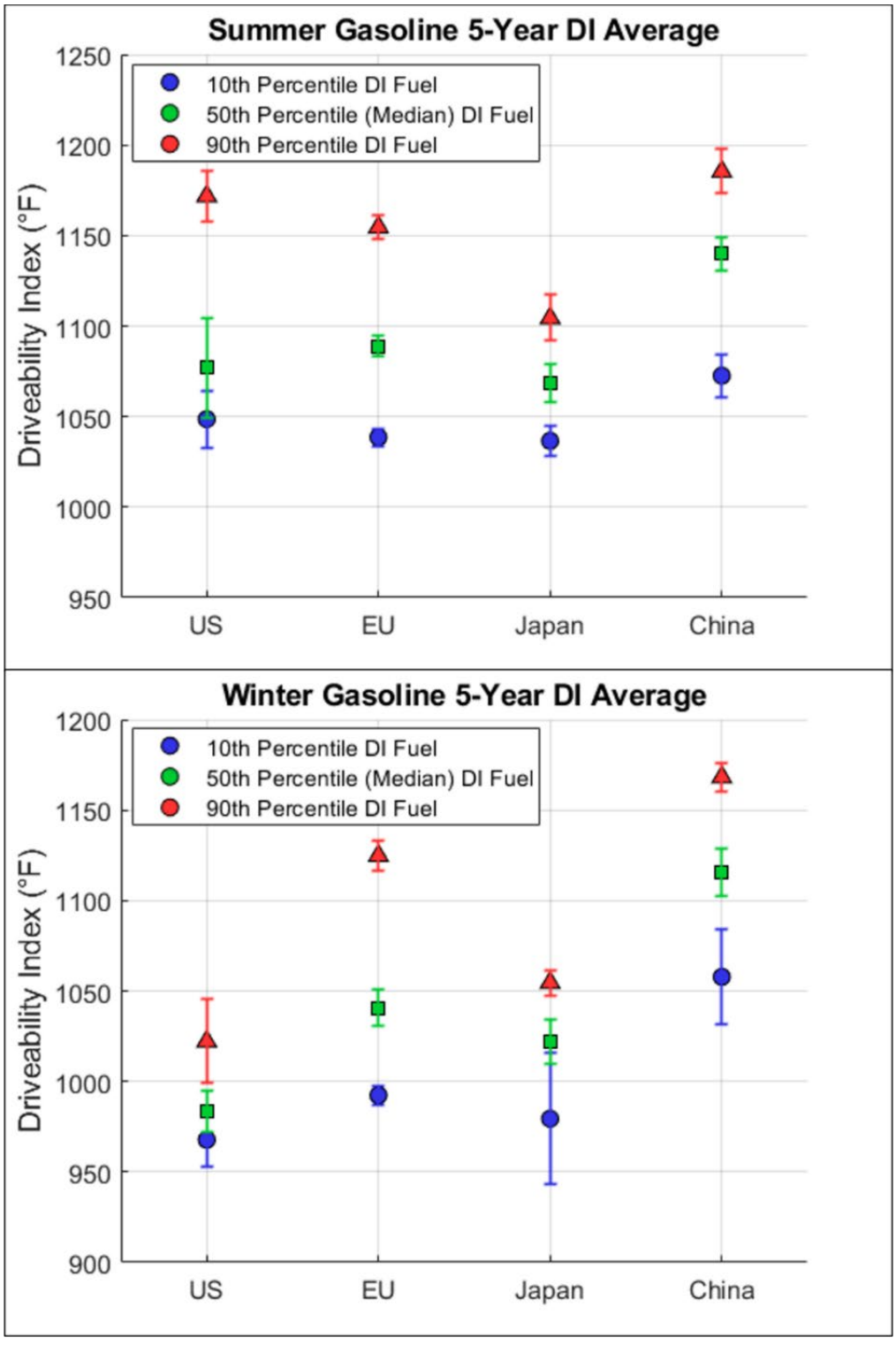


Figure 36: 5-year average of Driveability Index values for summer and winter (2020 – 2024)

Median DI Distillation Curves and Conformance of Fuels Across Regions

This section makes a comparison between the distillation curves of the median DI regular gasolines from the sample data for the United States, the European Union, Japan and China. Figure 37 shows the median distillation curves for the four countries for summer (top) and winter (bottom). The numbers used to denote the regular gasolines are based on the antiknock number (AKI or RON) used by each country to denote the fuel grade at gas stations.

- Front-end volatility: All winter gasoline samples have an IBP below 37.8° (100°F), which is the temperature at which DVPE is measured. The lower IBP during winter enables a higher DVPE. The median gasoline from Japan has the lowest IBP and T10 for both seasons.
- Mid-range volatility: The United States median summer and winter gasolines have the lowest T50 values of all four countries. This is likely due to the suppression of the T50 due to the 10% ethanol addition. This suppression can be observed in the samples from the EU as well, but to a lesser extent. The suppression depends on the hydrocarbon composition of the BOB. Median gasolines from China have the highest T50 values.
- Back-end volatility: Median gasoline from the US has the highest FBP for the summer and winter seasons. The distillation curves past the T50 point show a noticeable increase in slope, which points to the use of heavy hydrocarbons. A previous study conducted by General Motors [39] showed the importance of T70 for cold-start and warm-up driveability. Barring China, the US gasoline samples show the highest T70 and T90 values.
- The EU has more stringent particulate matter (PM) and particle number emission regulations, which could be a reason for the lower T90 and FBP.

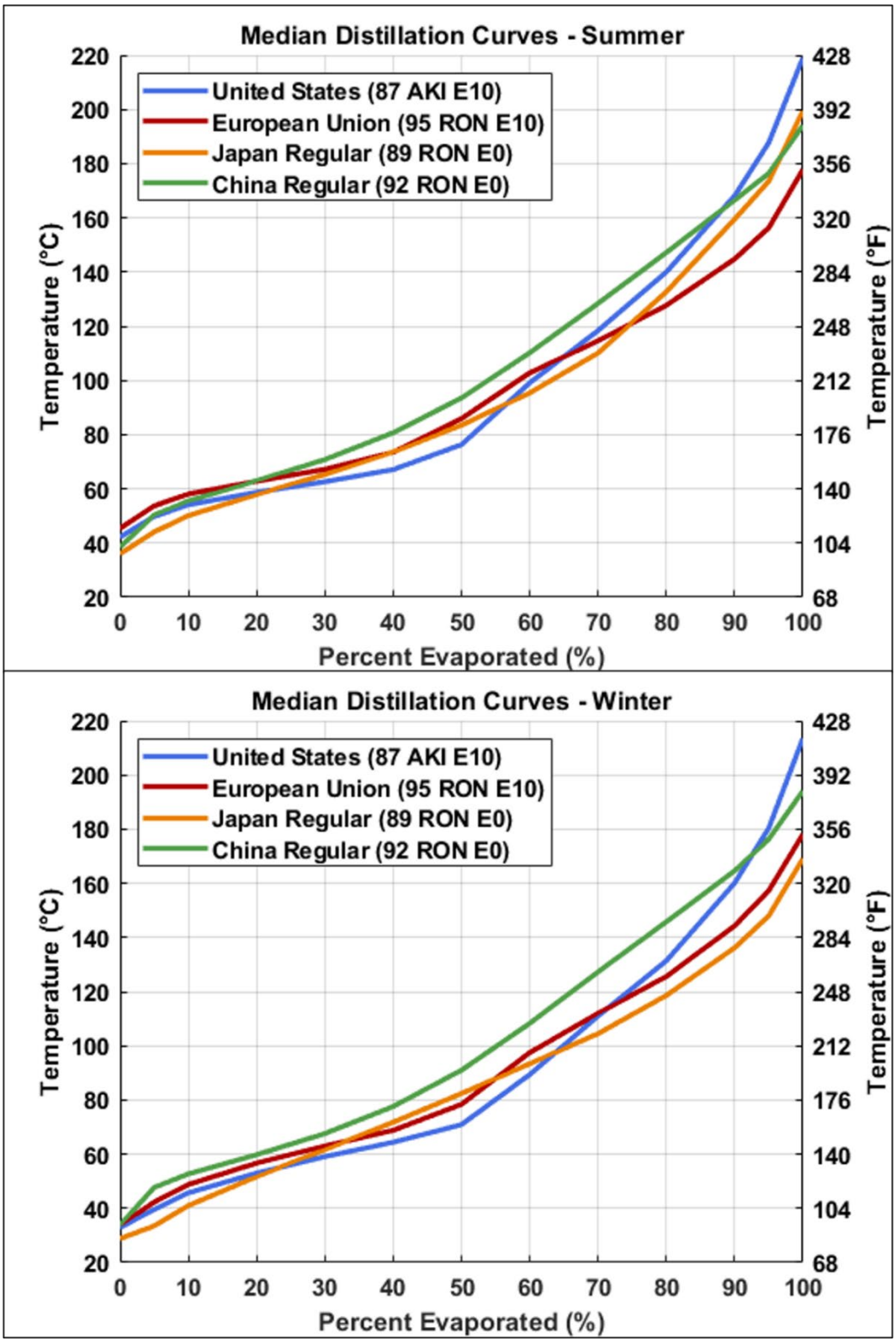


Figure 37: Distillation curves for median Driveability Index gasoline samples (summer and winter 2024)

Table 24 shows evaluation of the median gasolines from the EU, Japan and China on conformance to the US ASTM D4814 standard (Grade A for summer and Grade E for winter)[12]. The only occurrence of non-conformance is the T10 for the median winter gasoline sample from China. The T10 value of 52.2°C (126°F) is higher than the maximum for grade E gasoline from the ASTM D4814 standard value of 50°C (122°F). However, it is within the requirement of grade D gasoline. By and large, all median gasoline samples from the three additional regions analyzed are well within the US gasoline volatility requirements.

Table 24: Conformance of median DI gasoline samples from the EU, Japan and China (2024) to ASTM D4814 standard requirements

Summer					
	T10	T50	T90	FBP	DI
EU	Yes	Yes	Yes	Yes	Yes
Japan	Yes	Yes	Yes	Yes	Yes
China	Yes	Yes	Yes	Yes	Yes
Winter					
	T10	T50	T90	FBP	DI
EU	Yes	Yes	Yes	Yes	Yes
Japan	Yes	Yes	Yes	Yes	Yes
China	No	Yes	Yes	Yes	Yes

Table 25, Table 26 and Table 27 show the conformance of the US summer and winter gasolines for volatility requirements based on the EU, Japan and China standards respectively. The median US gasoline samples comply with all requirements except for the final boiling point for European EN228 specification (FBP 210°C) and the Chinese GB 17930-2016 specification (FBP 205°C). Final boiling point (also referred to as 'final distillation' point or 'end point' depending on the standard) for all grades of gasoline in the United States is 225°C. This can be tied back to the median distillation curves in Figure 37.

[12] Vapor pressure (DVPE) values of gasoline samples were not acquired. Hence, conformance checks on vapor pressure values have not been included.

Table 25: Conformance of US median DI gasoline (2024) to EN228 (the EU) standard requirements

Summer				
	E70 (%)	E100 (%)	E150 (%)	FBP (°C)
European Union Requirements	20 - 50	46 - 72	Min. 75	Max. 210
United States Median	44.4	60.4	83.9	219
US Median Gasoline Conformance	Yes	Yes	Yes	No
Winter				
	E70 (%)	E100 (%)	E150 (%)	FBP (°C)
European Union Requirements	22 - 52	46 - 72	Min. 75	Max. 210
United States Median	49.1	64.2	86.9	213.5
US Median Gasoline Conformance	Yes	Yes	Yes	No

Table 26: Conformance of US median DI gasoline (2024) to JIS K 2022:2023 (Japan) standard requirements

Summer				
	T10 (°C)	T50 (°C)	T90 (°C)	FBP (°C)
Japan Requirements	Max. 70	70 - 105	Max. 180	Max. 220
United States Median	54.1	76.3	168.1	219
US Median Gasoline Conformance	Yes	Yes	Yes	Yes
Winter				
	T10	T50	T90	FBP
Japan Requirements	Max. 70	70 - 105	Max. 180	Max. 220
United States Median	45.7	70.9	160.1	213.5
US Median Gasoline Conformance	Yes	Yes	Yes	Yes

Table 27: Conformance of US median DI gasoline (2024) to GB 17930-2016 (China) standard requirements

Summer				
	T10 (°C)	T50 (°C)	T90 (°C)	FBP (°C)
China Requirements	Max. 70	Max. 120	Max. 190	Max. 205
United States Median	54.1	76.3	168.1	219
US Median Gasoline Conformance	Yes	Yes	Yes	No
Winter				
	T10 (°C)	T50 (°C)	T90 (°C)	FBP (°C)
China Requirements	Max. 70	Max. 120	Max. 190	Max. 205
United States Median	45.7	70.9	160.1	213.5
US Median Gasoline Conformance	Yes	Yes	Yes	No

Although there are a few points of non-conformance, the median US gasolines are within the majority of requirements for the other three regions. The tables above show that even though there might be notable differences in the standards and the theoretical DI values calculated, the reality is that volatility parameters for gasoline samples from the four major automotive markets are quite close to one another.

Fuel Volatility Ties to Emissions Requirements

Fuel volatility has close ties to emissions requirements. Low volatility fuels require increased fuel enrichment for smooth driveability during cold start and engine warm-up. Fuel enrichment significantly increases the unburned HC and carbon monoxide (CO) emissions. In the wake of ever more stringent emission standards, fuel enrichment is not a strategy that can be deployed. The fuel volatility needs to be adequate to ensure good driveability as well as emissions compliance.

The current emission standards in the United States are the Tier 3 standards, which were introduced for MY 2017 vehicles and later. The emission standard and the CO emission limit for gasoline light duty vehicles are summarized below in Table 28.

Table 28 does not offer an equivalent comparison as the drive cycles for all regions are not the same. All regions show similarly stringent restrictions on CO emissions. To provide a basis for comparison, the CO emissions requirement in the United States until the start of the 1980s was 51 g/mile. That has been reduced by over 90% in the last 40 years.

Table 28: Carbon monoxide (CO) emissions requirements

Region	Emission Standard	Drive Cycle[A]	CO Emission Requirement (g/km (g/mile))
United States	Tier 3	FTP-75	2.61 - 0.62 (4.2 - 0)[B]
European Union	Euro 6d	WLTP	1 (1.61)
Japan	Japanese Light Duty Standards	JC08	1.15 (1.85)
China	China 6b	WLTP	0.5 (0.8)

[A]The FTP-75 and JC08 drive cycles include cold start, while the WLTP drive cycle does not.
[B]The United Tier 3 emission standards include a range of values for CO emissions from 4.2 g/mile to 0 g/mile depending on the bin of measurement.

The United States, EU and China have additional requirements for CO emissions for cold start at -7°C, shown in Table 29. As stated before, a direct comparison cannot be made due to variation in the test cycles.

Table 29: Carbon monoxide (CO) emissions requirements for cold start

Region	CO Emission Requirement (g/km (g/mile))
United States	6.2 (10)
European Union	15 (24.1)
China	10 (16.1)

Emissions requirements drive fuel volatility properties. An insufficiently volatile fuel increases emissions of CO, unburned hydrocarbons and particulate matter (PM). Cold start emissions requirements factor in the matter as well. A fuel can be within the volatility

requirements of the gasoline standards, but if it cannot meet the emissions requirements for CO, HC, and PM, the volatility parameters will require changes. The emissions requirements could be one of the major reasons why median gasolines from the US, the EU, Japan and China do not have a high variability in volatility parameters.

Summary

The gasoline volatility specifications from three major automotive markets besides the United States were analyzed.

- **The European Union**
- **Japan**
- **China**

Driveability Index is a parameter unique to the United States (amongst the four regions studied). The volatility requirements of these regions were compared with those of the United States to determine whether there are requirements similar to DI. Gasoline sample data was acquired from SGS Inspire to compare the spread of DI values (calculated for each region based on distillation temperatures and ethanol content). An analysis was conducted on whether the median DI gasoline samples from the United States fulfill the volatility requirements from the other three regions, and vice versa.

A summary of the volatility requirements of the four regions is shown below in Table 30.

Table 30: Gasoline volatility requirements for the United States, the European Union, Japan and China[13]

Summer	US	EU	Japan	China
T10 (°C)	70 max.	NA	70 max.	70 max.
T50 (°C)	77 - 121	NA	70 - 105	120 max.
T90 (°C)	190 max.	NA	180 max.	190 max.
FBP (°C)	225 max.	210 max.	220 max.	205 max.
E70 (%)	NA	20 - 50	NA	NA
E100 (%)	NA	46 - 72	NA	NA
E150 (%)	NA	75 min.	NA	NA
Vapor Pressure (kPa)	62 max.	45 - 60	44 - 78	40 - 65
Winter	US	EU	Japan	China
T10 (°C)	50 max.	NA	70 max.	70 max.
T50 (°C)	77 - 110	NA	70 - 105	120 max.
T90 (°C)	185 max.	NA	180 max.	190 max.
FBP (°C)	225 max.	210 max.	220 max.	205 max.
E70 (%)	NA	22 - 52	NA	NA
E100 (%)	NA	46 - 72	NA	NA
E150 (%)	NA	75 min.	NA	NA
Vapor Pressure (kPa)	103	70 - 100	44 - 78	45 - 80

The findings from this section are summarized below.

- Across the EU, Japan, China, and the United States, gasoline volatility requirements differ structurally (distillation-based for the US, Japan and China versus evaporation-based for the EU), but the resulting fuels exhibit broadly similar volatility characteristics.
- The Driveability Index specification is unique to the United States amongst the regions investigated.
- Although Japan and China allow theoretical DI values higher than ASTM D4814 (calculated using the distillation temperature limits from respective gasoline standards), real-world gasoline samples from all regions fall well within US DI limits.

[13] Table 30 includes values mentioned in each of the tables for standard and does take into account any caveats carved out depending on the oxygenate content or climate. Details can be found in the separate tables for each standard. For the US and EU, which have six volatility classes, the two extreme classes are used for summer and winter gasoline properties.

- Median DI fuels from the three regions conform to ASTM D4814 for the majority of the requirements. The only occurrence of non-conformance is for the T10 value for the winter gasoline sample from China.
- Median fuels from the United States conform to the majority of the volatility requirements from the three regions except for FBP limits for the EU and China.
- The convergence of effective volatility properties across markets likely reflects common constraints driven by emissions standards, cold-start performance, and requirements for modern combustion systems.

Conclusions

Driveability refers to the quality of the response of a vehicle to the driver's demand. At most times, driveability is smooth and event free, thanks to the decades of research that have gone into automotive engineering. But there is a possibility that the driver experiences driveability issues. This depends on the interaction between fuel properties – specifically volatility - and engine technology, vehicle calibration, combustion strategy, driver behavior and perception, and ambient conditions. The Driveability Index equation was created to help ensure that the fuel quality does not contribute to poor cold start and warm-up driveability when utilized under normal customer usage in production vehicles.

In assessing the continued relevance of the DI equation and its limits, the research conducted to develop Driveability Index was reviewed and analyzed while considering changes in vehicle and engine technology, and external factors such as emissions legislation since those studies. Although modern engine technology has decreased vehicle sensitivity to fuel volatility, the data does not suggest that DI has been rendered irrelevant. The significant technological advances and changes in tailpipe and evaporative emissions requirements do merit consideration of changes to the current DI formulation or its limits to more accurately reflect the needs of the current vehicle fleet. Ultimately, experimental research designed to test the relevance of the current DI equation and limits needs to be conducted to come to a concrete conclusion. As of now, however, Driveability Index remains a relevant and important parameter in modern gasolines and vehicles.

If DI is not relevant or the current limits are stricter than required, gasoline volatility properties are being over constrained. If changes to the fuel volatility specifications are to be made, the performance of the resulting fuel must first be verified on both current and legacy vehicles. Previous studies related to DI were essentially performed on vehicles representative of those eras. Although inferences can be made, the data cannot be used to conclusively determine whether the current driveability index model is relevant in modern vehicles, and hence, additional experimentation with modern vehicles and engines technologies is required to answer the question regarding the continued relevance of DI.

Discussions with fuel and calibration experts have shed light on the fact that the current DI equation and its limits have worked well in the last few decades. What requires further investigation is whether DI is still the best metric to regulate fuel volatility, or are there alternative volatility controls that would provide the same level of driveability protection while being less constraining on refiners.

The most recent cold start driveability study was adopted by the CRC in 2020 (CM-138-15-2). This project does not fully resolve the question of the relevance of DI for the following reasons:

- Driveability demerits were not measured. Cylinder pressure transducers were used to measure the COV of IMEP, but that was not correlated with the demerit system used in previous driveability studies, so it is unknown how many demerits the vehicles would have received.
- The test vehicle sample size was relatively small, where only 3 vehicles were tested in comparison to the 18 vehicles tested in the previous cold start driveability study [10].
- The drive cycle used in previous projects was modified during this project with the intent of increasing driveability issues, since the original drive cycle did not produce enough driveability issues to conduct an analysis on the ability of the cylinder pressure transducers to detect driveability issues.

Two key points can be taken from this study:

1. Driveability issues can be measured objectively with cylinder pressure transducers.
2. Modern vehicles are still sensitive to high DI fuels – driveability issues were observed with instrumentation in several tests, backed by the driver stating they were severe enough to be felt. Although the modified drive cycle, vehicle sample size, and absence of driveability demerit ratings do not give us the ability to say that driveability concerns would be perceived in real world conditions, the driveability issues observed do tell us that modern vehicles are still sensitive to high DI fuels.

Two earlier studies conducted in 2003 and 2013 investigated modifications to DI for ethanol-gasoline blends - up to 10% ethanol by volume (CRC Report 638 [9]) and with ethanol percentage between 10% and 20% (CRC Report 666 [10]) respectively.

These projects achieved their objective, which was formulating a correlation so that ethanol's impact on gasoline properties is accounted for in the DI equation. However, neither of them evaluated the base DI equation. Instead, the outcome of the two projects was to add an offset term to the DI equation based on ethanol contribution. Additionally, the driveability results between the two showed different effects from ethanol addition. This difference in results could be attributed to two factors:

- Variations in base hydrocarbon constituents and DI values between the studies caused the ethanol to impact the fuel volatility parameters differently. The API study lays out these differences through fuel property analysis [76]. The results from CRC

Report 638 and CRC Report 666 demonstrate those effects on the impact of driveability.

- There was a span of ten years between the projects, and during that time, both vehicle technology and emissions standards developed significantly.
    - Vehicle Technology: CRC-638 used vehicles with, “various types of fuel injection”, (none being carbureted or GDI) and CRC-666 included a mix of vehicles with 4 GDI and 14 PFI. Even with both programs using mainly PFI vehicles, as discussed in the vehicle technology section, significant developments within those vehicle fuel systems and controls were made in the time between test programs.
    - Emissions Standards: Vehicles in the two projects were calibrated to different emissions standards; as a result, the CRC-666 vehicles had reduced authority for fuel enrichment during cold-start and warm-up operation.

Another 12 years have passed since the CRC-666 study, where significant improvements in vehicle technology and controls have been made, most notably to GDI and fuel adaptive controls. Also, similar to the previous gap between projects, vehicles now must conform to Tier 3 emission standards, with more stringent HC, CO, and particulate emissions limits further restricting enrichment during cold-start and warm-up operation. Regardless of the demerits measured in past projects, vehicle technology has now evolved to the point where the conclusions drawn in previous studies may not apply to current vehicles. This also points to inconsistencies with the DI equation’s ethanol modifier, where additional metrics or larger data sets could be used to improve the correlation between the current DI equation and vehicle driveability.

Not only have vehicles, fuel, and emissions standards changed, but so have humans. Driveability is based on the perception of humans and it is difficult to predict how much that perception has changed since the original DI equation was created, considering the last customer perception study was conducted in 1993 [8]. For example, if the average, modern American drove a carbureted vehicle from the early 1980’s, they would almost certainly report higher demerits than someone who has only ever driven vehicles from the 1980s.

Finally, stepping back to 1970s through 1990s, the CRC projects that gathered data and created the original DI equation were conducted on a vastly different vehicle fleet and ethanol had yet to gain prominence in the fuel market. The correlations made to create the original DI equation were sound and have continued to work, but the changes in every aspect of the driveability system since that time require new data to determine the relevance of the DI equation.

In reviewing the standards from regions around the world, it is noted that the European Union, Japan or China, do not have a direct equivalent to Driveability Index. Instead, these regions use other volatility metrics like distillation points and vapor pressure to control fuel volatility. Reviewing fuel data obtained from SGS INSPIRE [12] shows that the median DI gasoline samples from the United States are cross compatible with those from the other three regions, where U.S. fuels meet their fuel volatility requirements, and vice versa. It must be noted, though, that these other regions have differences in driver expectations and perception of driveability, climate, oil feedstock, and demand for the various refinery output streams. Also, if a high DI fuel has never been put into the market in these regions – due to any of the reasons above – they would never see a need for the creation of the standard.

Previous studies have shown that parameters including HoV, different distillation temperatures, or evaporative points, show strong correlation with driveability and could increase the fidelity of the correlation to TWDs [35].

One factor that has not been studied in detail is the emissions effects from high DI fuels or poor driveability, where the compensation for high DI fuels (enrichment) could potentially cause increased exhaust emissions. Modern vehicles may be able to adapt to high DI fuels, but studies need to be performed to understand what impact these adaptations would have on off-cycle emissions.

The above discussion summarizes that the system of driveability has changed and therefore an experimental program is needed to determine whether the current Driveability Index equation and limits remain relevant in modern vehicles, and whether alternative volatility metrics could provide equal or better correlation to TWDs. The program must first build a validated drive cycle for the assessment of driveability and correlate an objective measurement of TWDs to customer perception of driveability. Finally, the program must evaluate fuel volatility-vehicle interactions across a representative range of fuels and vehicle technologies. The program recommendations are summarized below.

1. **Drive Cycle Establishment and Validation**

Previous driveability studies used different drive cycles or modified the previous drive cycles to obtain demerits and achieve their program goals. These changes, however, make it difficult to make a direct comparison between programs as they can alter the propensity for generating demerits. A realistic and repeatable drive cycle must be developed or adopted to represent real world cold-start and warm-up conditions where driveability issues are most likely to occur. The cycle should:

- Reflect current vehicle operating patterns
- Elicit cold-start and transient behaviors relevant to DI sensitivity

- Be repeatable across laboratories and future studies

This drive cycle will create a foundation on which objective and subjective measurements can be correlated and should be used in future studies to allow for direct comparisons between test programs.

2. **Correlation of Customer Perception and Objective Measurement**

A customer perception study is needed to correlate the objective measurement of driveability demerits to the human perception of driveability demerits. Building off the work of the CRC 2020 program, spark plug cylinder pressure transducers and, as recommended, accelerometer measurements can be used in parallel with drivers to correlate the subjective human rating to the objective measurements from instrumentation. Multiple vehicles with different architectures should be used to ensure the different vehicle transfer functions and adaptive capabilities are well correlated with TWD rating.

The creation of an objective demerit system is essential for:

- Defining thresholds that constitute a driveability demerit
- Enabling consistent evaluation of driveability independent of variations in driver perception

This stage creates the measurement system needed for evaluating the relevance of DI in modern vehicles through an experimental study and allows for future test programs to compare results in an objective manner.

3. **Evaluation on the Relevance of DI in Modern Vehicles**

With a standard drive cycle and objective measurement system created, a study should be conducted to determine whether the current DI equation is relevant for today's vehicle fleet. This testing should include:

- Modern vehicles representing a broad range of vehicle technologies and vehicle architecture
- Representative market fuels with a range of DI below, near, and above the current limit, and varying ethanol concentrations
- An additional fuel set with equivalent DI and different distillation points

This program will provide data needed to determine if DI is still correlated to good driveability in modern vehicles and if the current limits are appropriate.

4. **Studies on Alternative Metrics, Adaptivity, and Ethanol Behavior**

Apart from the determination of the relevance of DI in modern vehicles, the findings in the literature review point to several other possibilities for controlling fuel volatility in order to maintain good driveability for cold-start and warm-up operation. These programs could be conducted concurrently with the evaluation on the relevance of DI, or after, if it is determined that the current DI metric lacks correlation or if it is excessively constraining gasoline volatility. The following studies are recommended based on our findings and should be conducted only after completing stages 1 and 2 above:

- **Investigation of Alternative Volatility Metrics**

A program designed to evaluate the use of different fuel volatility metrics, or to make modifications to the current volatility specifications in the DI equation. The volatility metrics used in other countries or regions should be a part of the investigation. This work would be structured similarly to the original driveability investigations where fuel properties are compared to measured vehicle demerits to create a correlation.

- **Evaluation of Adaptive Engine Controls on Sensitivity to Fuel DI**

Conduct a program to investigate the advanced controls of modern vehicles' ability to "learn" and adapt to different fuels and the adaptations impact on emissions. This study would require a broad range of vehicle technology in order to test the abilities of each adaptive technology. The most recent CRC driveability study conducted in 2020 (CM-138-15-2) [6] found that, in some cases, vehicle driveability improved after repeated tests with the same fuel and vehicle, where data analysis showed the fuel trims had adapted to the high driveability fuels. This suggests the possibility of increasing DI limits if modern vehicles are capable of adapting to the fuels. As the typical method for adaptation to insufficient volatility is enrichment, the emissions effect from these adaptations could also be included in this study.

The studies conducted since the original DI research have provided valuable insight into fuel volatility behavior, ethanol effects, and the maintained relevance of fuel volatility effects on modern vehicles. However, none were designed to directly evaluate the continued relevance of Driveability Index itself. Changes in vehicle technology, emission standards, fuel composition, and consumer perception have introduced uncertainty into the modern system of driveability. International fuel standards and the analysis of previous DI studies demonstrate that alternative volatility metrics could be effective in controlling fuel quality for acceptable driveability. The 2020 CRC study [6] showed that modern vehicles still exhibit sensitivity to high-DI fuels under certain conditions. Recent studies and discussions with subject matter experts from the automotive industry suggest that fuel volatility still plays a

prominent role in keeping the vehicle within the bounds of acceptable driveability and emissions requirements. There is evidence to conclude that fuel volatility control is still relevant, although the degree of that relevance is unknown. Also, previous experimental programs point to the possibility that other metrics - or modifications to the current DI equation or limits - could provide equivalent, or improved correlation while easing gasoline refining constraints.

Until representative data is collected, it is not possible to conclude whether DI is obsolete, remains essential, or could be replaced by alternative metrics that offer equal or better driveability protection while reducing constraints in the fuel manufacturing process. This report recommends that a targeted experimental study using validated objective measurements, modern vehicles, realistic drive cycles, and precise fuel-property variation be conducted to determine the relevance of the current Driveability Index equation within the modern system of driveability.

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Abbreviations and Definitions

ADAS – Advanced Driver Assistance Systems
AFR – Air-Fuel-Ratio
AKI – Anti-Knock Index
API – American Petroleum Institute
APSRC – Advanced Power Systems Research Center
ASTM – ASTM International
BOB – Blendstock for Oxygenate Blending
CAA – Clean Air Act
CFR – Code of Federal Regulations
CO – Carbon Monoxide
COV – Coefficient of Variation
CRC – Coordinating Research Council
CWD – Cold Weather Driveability
DN – Driveability Number
DI – Driveability Index
DISI – Direct Injection Spark Ignition
DVPE – Dry Vapor Pressure Equivalent
E0 – Gasoline with 0% Ethanol by Volume
E10 – Gasoline with 10% Ethanol by Volume
E15 – Gasoline with 15% Ethanol by Volume
Exx – Percentage of fuel evaporated at 'xx' deg C (or deg F)
EDI – Evaporative Driveability Index
EISA – Energy Independence and Security Act
EPA – Environmental Protection Agency
ETBE – Ethyl Tertiary-Butyl Ether
EU – European Union
FTP – Federal Test Procedure
FBP – Final Boiling Point
GDI – Gasoline Direct Injection
HC - Hydrocarbons
HEV – Hybrid Electric Vehicle
HoV – Heat of Vaporization
HWD – Hot Weather Driveability
IBP – Initial Boiling Point
IMEP – Indicated Mean Effective Pressure
IC – Internal Combustion

JC08 – Drive cycle used in Japan for emissions certification
LEL – Lower Explosive Limit
LSPI – Low-Speed Pre-Ignition
MBT – Maximum Brake Torque
MHEV – Mild Hybrid Electric Vehicle
MON – Motor Octane Number
MTBE – Methyl Tertiary-Butyl Ether
MTU – Michigan Technological University
MY – Model Year
NMOG – Non-Methane Organic Gases
NOx – Oxides of Nitrogen
OEM – Original Equipment Manufacturer
OHC – Overhead Cam
PCV – Positive Crankcase Ventilation
PEI – Particulate Emissions Index
PFDI – Port Fuel and Direct Injection
PFI – Port Fuel Injection
PHEV – Plug-in Hybrid Electric Vehicle
PM – Particulate Mass
PMI – Particulate Matter Index
PN – Particle Number
RFG – Reformulated Gasoline
RFS – Renewable Fuel Standard
RON – Research Octane Number
RVP – Reid Vapor Pressure
SFI – Sequential Fuel Injection
SI – Spark Ignition
SIDI – Spark Ignition Direct Injection
SME – Subject Matter Expert
SPI – Stochastic Pre-Ignition
SwRI – Southwest Research Institute
T10 – Temperature at 10% Evaporated
T50 – Temperature at 50% Evaporated
T90 – Temperature at 90% Evaporated
Txx – Temperature at which xx% of fuel is evaporated
$T_{V/L=20}$ – Vapor–Liquid Ratio Temperature at 20
TBI – Throttle Body Injection
TWD – Total Weighted Demerits

UK – United Kingdom
US – United States
VVT – Variable Valve Timing
WLTP – Worldwide Harmonized Light Vehicles Test Procedure
WUI – Warm-up Index

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Appendix

CRC Test Procedure for Driveability Studies

1. Cold Start and Driveaway Schedule I

This test technique, described in detail in Appendix B, provides for starting the car after an overnight cold soak, idling for five seconds at each of three conditions, and then driving through a series of maneuvers which are repeated, with some change after three cycles, for a total of ten cycles.
The three idling conditions include: transmission in neutral with throttle on the fast idle cam, in neutral with throttle off the fast idle cam, and in drive with throttle off the fast idle cam.
The first three driving cycles include:

1. Light, part throttle, 0 to 25 mph acceleration
2. Cruise at 25 mph
3. Part throttle to detent 25 to 35 mph acceleration
4. Wide open throttle 0 to 35 mph acceleration
5. Light part throttle 10 to 25 mph acceleration
6. A 30-second idle period with transmission in drive

For the last seven cycles, a 0 to 45 mph acceleration at crowd condition (constant vacuum) replaces the first part throttle acceleration and the 25 mph cruise. Any stalls are recorded, and idle roughness, hesitation, stumble, surge, and backfiring are rated subjectively on a scale of Satisfactory (S), Trace (T), Moderate (M), or Heavy (H).
If a stall in any maneuver was accompanied by idle roughness, hesitation, stumble, or surge, only the stall (the most severe malfunction) was recorded.

2. Cold Start and Driveaway Schedule II

An alternate procedure intended to protract the warm-up period and to include measurements of accelerating ability was devised on site at Pasco and evaluated in five cars. The procedure, detailed in Appendix F, included start-up and initial idling evaluation as in Schedule I.
This was followed by 30 cycles consisting of a cruise for 0.10 mile at 20 mph, acceleration from 20 to 40 mph at part throttle detent, and deceleration to 20 mph in another 0.10 mile.
Malfunctions were recorded the same as for Schedule I and, in addition, the 20 to 40 mph acceleration time was recorded for each cycle.

3. Warmed Up Schedule III

Performance is evaluated in eight different maneuvers, some performed at several speeds and/or throttle conditions.
These are followed by additional warm-up driving, a fifteen-minute soak period, and then an evaluation of hot start and run characteristics.

The initial maneuvers include idling, engine acceleration at standstill against the torque converter, cruise at road load, wide open throttle accelerations, and part throttle accelerations at fixed throttle, crowd, and tip-in conditions.
Performance in these maneuvers is rated in a manner similar to Schedule I, with the additional observation of stretchiness on a yes or no basis during cruise.

Since the ten-mile highway warm-up run was completed a few miles from the test track, some maneuvers were executed on the highway and some on the test track.
Also, since the order of the maneuvers was not important, they were not necessarily executed in the same sequence, as listed in the data sheet (Appendix E).

Modifications to the Procedure in Appendix B

Modifications to the procedure in Appendix B adopted on site were as follows:

1. The maximum speed was changed from 70 mph to 60 mph to comply with local speed limits.
2. The procedure in Appendix B calls for a wide open throttle acceleration against the torque converter. This was changed to opening the throttle to the power enrichment vacuum point to prevent unnecessary strain on the drive line. Any malfunction would be noticed before this point was reached.

Summary of Test Method as stated in ASTM D86 (Measurement of the Distillation Curve and Distillation Temperatures)

stated below and the apparatus as shown in ASTM D86 is shown in Figure 38.

1. Based on its composition, vapor pressure, expected IBP or expected EP, or combination thereof, the sample is placed in one of four groups. Apparatus arrangement, condenser temperature, and other operational variables are defined by the group in which the sample falls.
2. A 100 mL specimen of the sample is distilled under prescribed conditions for the group in which the sample falls. The distillation is performed in a laboratory batch distillation unit at ambient pressure under conditions that are designed to provide

approximately one theoretical plate fractionation. Systematic observations of temperature readings and volumes of condensate are made, depending on the needs of the user of the data. The volume of the residue and the losses are also recorded.

3. At the conclusion of the distillation, the observed vapor temperatures can be corrected for barometric pressure and the data are examined for conformance to procedural requirements, such as distillation rates. The test is repeated if any specified condition has not been met.
4. Test results are commonly expressed as percent evaporated or percent recovered versus corresponding temperature, either in a table or graphically, as a plot of the distillation curve.

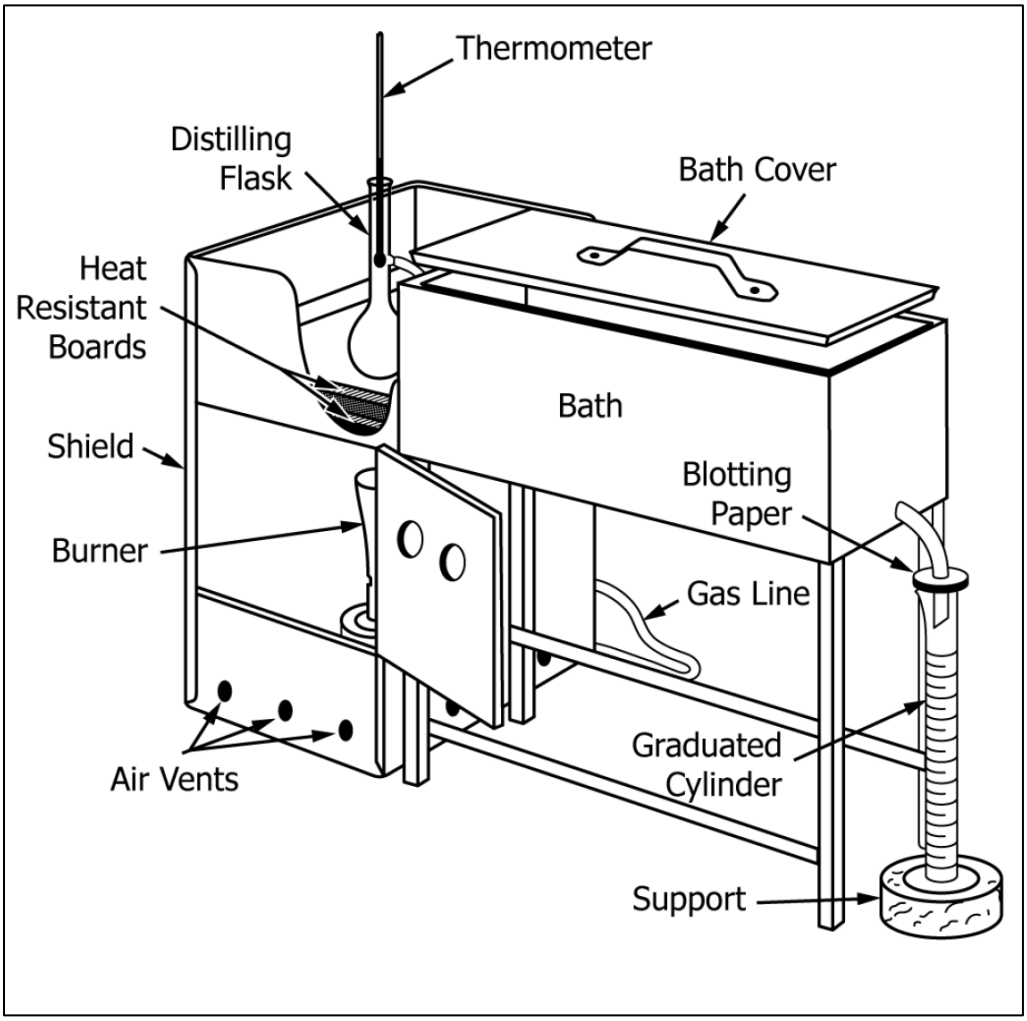

Figure 38: Apparatus used in ASTM D86 to determine the distillation curve of a fuel

Summary of Test Procedure as stated in ASTM D5191 (Measurement of Vapor Pressure)

1. A known volume of chilled, air-saturated sample is introduced into a thermostatically controlled, evacuated test chamber, or a test chamber with a moveable piston that expands the volume after sample introduction, the internal volume of which is five times that of the total test specimen introduced into the chamber. After introduction into the test chamber, the test specimen is allowed to reach thermal equilibrium at the test temperature, 37.8 °C (100 °F). The resulting rise in pressure in the chamber is measured using a pressure transducer sensor and indicator. Only total pressure measurements (sum of the partial pressure of the sample and the partial pressure of the dissolved air) are used in this test method, although some instruments can measure the absolute pressure of the sample as well.
2. The measured total vapor pressure is converted to a dry vapor pressure equivalent (DVPE) by use of a correlation equation.

Summary of Test Procedure as stated in ASTM D5188 (Measurement of $T_{V/L=20}$)

A known volume of chilled, air-saturated sample is introduced into an evacuated, thermostatically controlled test chamber of known volume or a test chamber with moveable piston that expands the volume after sample introduction, the internal volume of which is V/L+1 times of that of the total test specimen introduced into the chamber. The sample volume is calculated to give the desired vapor-liquid ratio for the chamber volume in use. After injection, the chamber temperature is adjusted until a stable chamber pressure of 101.3 kPa (14.69 psia) is achieved.

Regulatory and Standards Framework as Applied to the Fuel Supply Chain

This section is intended to give a brief overview of how laws and standards are developed, implemented, and enforced in the U.S. The scope for this report is on the science and engineering, but this section was written to help the reader understand the intricacies of U.S. policy and rulemaking. To state it simply: standards used to enforce fuel quality at a national level must be tied to public health or safety concerns and cannot be arbitrary or capricious. This means that a standard must be adopted under the authority of a law in order to be enforceable.

- **Agencies**

The Federal government has organizations called agencies which help carry out functional duties. Some agencies are non-regulatory and support administration and research. The National Institute of Standards and Technology (NIST) is a part of the U.S. Department of Commerce which was created to standardize the U.S. measurement infrastructure. NIST publishes standards that can be voluntarily adopted by federal, state, or local organizations so consistent definitions, measurements, and labeling are used throughout the manufacturing and sale of a product or service.

Other agencies are granted the power to create and issue legally binding rules. The Environmental Protection Agency (EPA) is an example of a federal agency which has been granted the authority to write regulations to protect human health and environment. Most of the EPA's current laws concerning vehicles get their authority from the Clean Air Act (CAA) which was enacted by Congress in 1970. This law allows the EPA to regulate air pollution, including emissions from vehicles. Since automobile pollution regulation was nearly non-existent, the EPA performed much of its own research into pollution control and standards development.

- **Standards Organizations**

To reduce costs and streamline the creation and adoption of laws, governments rely on Voluntary Consensus Standards to simplify requirements and incorporate industry practices into their rulemaking. These standards are created through a structured process that is open to all stakeholders and considers the input of all interested parties. Standards are important because they form a common set of expectations that are acceptable to the various while reducing proliferation and duplicate work when While Standards don't have any legal authority on their own, a well-written standard will often be "incorporated by reference" into law because the authorities having jurisdiction (i.e., governing bodies) have confidence that the standard was acceptable by stakeholder consensus.

The EPA relies on ASTM International (formerly the American Society for Testing and Materials) to develop and publish Testing Methods, Fuel Specifications, Guides, and Practices.. ASTM is a scientific and technical organization formed for "the development of standards on characteristics and performance of materials, products, systems, and services; and the promotion of related knowledge." It is the world's largest source of voluntary consensus standards.

- **Councils**

In the early years of the U.S., the states created laws and rules to address needs and concerns within their borders. As the nation grew, the lack of uniformity became apparent,

so councils were formed to bring the states together in discussions to address the lack of oversight.

The National Council on Weights and Measures (NCWM) is a non-profit organization that has been around since 1905 and develops standards that NIST then publishes for adoption by the states.

The Coordinating Research Council (CRC) is a non-profit organization that directs, through committee action, engineering and environmental studies on the interaction between automotive/other mobility equipment and petroleum products. CRC supports both cooperative large-scale research programs that are executed by members and contracted research that is executed by other research organizations.

- **Fuel Volatility and Driveability**

While the focus of this report is on the Driveability Index of gasolines, there are many regulated aspects of gasoline that can impact the chemical composition (and therefore the combustion) of the spark ignited engine. Federal regulations regarding gasoline quality were developed to protect consumers of interstate commerce, most of which can be found in the EPA's 40 CFR Part 1090 Subpart C where pollution from IC engines is addressed by limiting sulfur, RVP, ethanol, butane, etc. The EPA published Table 31 in August 2025 [97] to explain the rationale behind each gasoline fuel program.

Table 31: Programs and pollutants [97]

Regulatory Program	Overview	Pollutants Addressed
Sulfur Content in Gasoline	Limits the sulfur content in gasoline which allows for cleaner burning fuel and use of advanced emissions control technologies in cars and trucks. This program is implemented at the federal level.	Smog (ground level ozone); particulate matter
Air Toxics Standards for Gasoline	Limits the content of toxic chemicals in gasoline. This program is implemented at the federal level.	Benzene; other hydrocarbons such as 1,3-butadiene, formaldehyde, acetaldehyde, acrolein, naphthalene
Reformulated Gasoline	Requires use of specially blended gasoline that evaporates less at higher temperatures than regular gasoline during the summer. This reduces emissions of volatile organic compounds that contribute to higher levels of ground level ozone in the hot summer months. RFG is more effective at reducing emissions of volatile organic compounds than low Reid Vapor Pressure gasoline. This program is implemented at the state and local level with federal oversight by EPA.	Ground level ozone (Smog)
Low Reid Vapor Pressure Gasoline	Requires use of specially formulated gasoline that evaporates less at higher temperatures than regular gasoline. This reduces emissions of volatile organic compounds that contribute to higher levels of ground level ozone in the hot summer months. This program is implemented at the state and local level with federal oversight by EPA.	Ground level ozone (Smog)
Winter Oxygenates	Mandates addition of an oxygenate (usually ethanol) to gasoline in the winter which reduces inefficient combustion of fuel during cold weather and can result in higher emissions of carbon monoxide. This program is implemented at the state and local level with federal oversight by EPA.	Carbon monoxide

While the EPA rules apply to gasoline sold across state lines, each state has the authority to set gasoline quality standards for their own fuels. Some states define the parameters for fuel volatility in their own laws, but more than 75% of the states adopt the “Standard Specification for Automotive Spark-Ignition Engine Fuel” (ASTM D4814) either directly from ASTM or through adoption of the “uniform engine fuels and automotive lubricants regulation” from the NIST Handbook 130. Half of these states automatically adopt the latest version of D4814 as it is published.

D4814 is published by ASTM’s D02 committee on Petroleum Products, Fuels, and Lubricants and sets specifications for gasoline’s volatility, distillation curve, and other key properties. It

ensures that automotive gasolines will work in IC engines across different regions and seasons.

The NIST Handbook 130 (titled Uniform Laws and Regulations in the Areas of Legal Metrology and Fuel Quality) includes a compilation of model laws and regulations and related interpretations and guidelines designed to encourage uniformity in adoption and implementation of weights and measures laws and regulations. This handbook is developed by the Fuels and Lubricants Subcommittee (FALS) of NCWM and lays out hundreds of standards for fuel quality, including specifications for meeting the latest version of ASTM D4814 (Section 2.1)

Details of CRC Driveability Studies Used in the Report

The work done by the CRC has played an important role in the decisions around gasoline volatility requirements in the United States. Table 32 includes details of all the CRC studies relevant to this report that have been referenced in the report.

Table 32: Details of CRC driveability studies referenced in the report

Publication Year	Report Number	Location	Ambient Temperature Range	Fuels	Vehicles
1970	CRC 439	Pasco, Washington	30°F – 50°F	4 fuels with a mix of two T50 (190°C and 230°C) and two RVP (6 psi and 9 psi) values	16 vehicles; all MY 1969; carbureted; automatic transmission
1975	CRC 483	Yuma, Arizona	40°F – 50°F, 60°F – 70°F	9 fuels, two level factorial with three controlled variables (T10, T50, and T90)	16 pairs of MY 1973 cars (total of 32 cars), one for each ambient condition; carbureted; automatic transmission
1976	CRC 486	Camp Roberts, California	40°F – 50°F, 60°F – 70°F	9 fuels, two level factorial with three controlled variables (T10, T50, and T90)	16 pairs of MY 1975 cars (total of 32 cars); carbureted; automatic transmission; equipped with California emission control systems
1978	CRC 499	Paso Robles, California	40°F – 70°F	3 fuels with low, intermediate, and high volatilities	40 vehicles; carbureted; 35 equipped with Federal emission control systems, 5 equipped with California emission control systems
1980	CRC 512	San Antonio, Texas	30°F – 70°F	3 fuels with low, intermediate, and high volatilities	107 vehicles; MY 1973 to MY 1978
1982	CRC 524	Brainerd, Minnesota	-20°F – 28°F, 40°F – 69°F	9 fuels, two level factorial with three controlled variables (T10, T50, and T90)	16 cars, all MY 1980, 10 cars with closed-loop fuel systems, carbureted 6 cars with open-loop fuel systems

1993	CRC 585	San Antonio, Texas	40°F – 68°F	10 fuels; hydrocarbon only fuels, gasoline-ethanol blends and, gasoline-MTBE blends	167 vehicles, fuel systems included carbureted, PFI and TBI
1997	CRC 599	Yakima, Washington	32°F – 53°F	30 fuels; hydrocarbon only fuels, E10 fuels and 15% MTBE fuels; varying DVPE and distillation temperatures	45 vehicles; MY1995 and MY 1996; fuel systems included TBI, PFI and central point injection
1998	CRC 603	Yakima, Washington	62°F – 84°F	29 fuels; hydrocarbon only fuels, E10 fuels and 15% MTBE fuels; varying DVPE and distillation temperatures	45 vehicles; MY1995 and MY 1996; fuel systems included TBI, PFI and central point injection
1998	CRC 605	Brainerd, Minnesota	-8°F – 32°F	29 fuels; hydrocarbon only fuels, E10 fuels and 15% MTBE fuels; varying DVPE and distillation temperatures	45 vehicles; MY1995 and MY 1996; fuel systems included TBI, PFI and central point injection
1998	CRC 613	Summary of CRC 599, CRC 603 and CRC 605			
2004	CRC 638	Yakima, Washington	14°F – 41°F	10 fuels; E0, E6 and E10 fuels; all fuels with DVPE approximately 55 kPa (8 psi); all fuels with DI values over 1250°F before ethanol correction	27 vehicles; MY 2002 and MY 2003
2008	CRC 652	Yakima, Washington	20°F – 50°F	8 fuels; E0, E15, E20, E85 fuels; varying DVPE values	20 flex fuel vehicles, MY 2000 to MY 2006; 6 regular vehicles, MY 1981 to MY 2007
2009	CRC 654	Sarnia, Ontario, Canada	-20°F – 20°F	8 fuels; E0, E75, E85 fuels; varying DVPE values	20 flex fuel vehicles; MY 2007 and MY 2008,
2011	CRC 659	Pueblo, Colorado	93°F – 109°F	7 fuels; E10, E10, and E20 fuels; varying T50, TVL20, and DVPE values	20 vehicles; MY 2009 and MY 2010
2014	CRC 666	Yakima, Washington	35°F – 45°F	10 fuels; 4 E0 fuels, 2 E10 fuels, 2 E15 fuels, 2 E20 fuels; varying DVPE values	18 vehicles; MY 2012 and MY 2013; 13 PFI, 5 GDI
2015	CRC 668	Yuma, Arizona	65°F – 120°F	16 fuels; E10 and E15 fuels; DVPE varying from 56 kPa to 112 kP 98 psi to 12 psi)	18 vehicles; 1 MY 1999, 1 MY 2003, remaining 16 MY 2013 and MY 2014; 16 PFI, 2 GDI