Effects of Ethanol Blends on Light-Duty Vehicle Emissions: *A Critical Review*

FINAL REPORT

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Study Team:

Nigel Clark, Consultant
Terry Higgins, Consultant, THiggins Energy Consulting
David McKain, Consultant
Tammy Klein, Principal Consultant, Future Fuel Strategies

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Executive Summary

Studies that have examined the effect on passenger and light-truck tailpipe emissions of adding ethanol to gasoline at low- and mid-levels were reviewed comparatively and against real-world application. Only studies addressing vehicles that are major components of the fleet were considered because automotive technology has advanced substantially in the last two decades. Gaseous emissions have been reduced steadily, in response to tighter standards. In particular, gasoline direct injection (GDI) engines differ from port fuel injected (PFI) engines. GDI vehicles emit higher levels of PM, but the PM is being reduced at time of writing. Studies have used different test cycles, particularly the FTP and LA92, and these have been reviewed. Refinery practices dictate the streams available for blending the real-world blendstock for oxygenate blending (BOB) to which the ethanol is added. These streams include FCC Gasoline, Reformate, Alkylate, Aromatics, and Butane, and additional smaller streams, such as Light Straight Run Naphtha. Most ethanol is blended at the 10% volume level to yield E10 pump fuel. Expansion of E15 use is contemplated.

Ethanol, when added to gasoline or a Blendstock for Oxygenate Blending (BOB), raises octane rating, alters the distillation curve, and raises the vapor pressure: blending properties are generally nonlinear. The effect of ethanol between 0% (E0) and 10% (E10) differs substantially from the effect between E10 and E20: change in major blend properties is far from linear. About 6% of ethanol involves splash blending with pump gasoline. Most ethanol is blended with a BOB to produce gasoline for sale at the pump. Refineries lower the octane of the BOB, with reduced aromatic content, to take advantage of the high-octane blend characteristics of ethanol. Since the introduction of ethanol blends starting in 2006, aromatics in U.S. pump fuel have dropped from about 28% (for E0) to about 21% for E10, while maintaining similar octane ratings. Many of the blends used in emissions studies do not reflect typical makeup of in-use fuels.

Studies have examined ethanol effects on post-catalyst tailpipe emissions, including carbon monoxide (CO), total hydrocarbons (THC), and oxides of nitrogen (NOx). Many have also examined PM, and a few have addressed particle number and composition, with increasing interest in GDI engine exhaust. Some have addressed air toxics, including benzene and aldehydes.

Major studies reviewed include the Coordinating Research Council E-67 and E-94 studies, the EPAct study, and studies by the US Department of Energy national laboratories. Numerous smaller studies were also reviewed. They include splash-blended studies, where only the level of ethanol addition was varied, and studies where specific properties are targeted for match blending. Most match blended studies seek to determine the effect of several variables, using a multivariate analysis approach. For example, ethanol, aromatics, the 50% distillation temperature (T50), T90 and a Particulate Matter Index (PMI) have all been examined for effect. In some of these studies, the fuels have been blended to satisfy a rigid matrix of values for the study variables, leading to test fuel compositions that do not mimic the real world and distillation curves. In these cases, it is unknown how properties that are not considered as study variables impact the statistical analysis that is employed.

Results from the studies were compared. It was clear that automotive technology evolution caused disagreement in absolute values of emissions reported over the two decades of the studies. However, the relative emissions for differing ethanol blends from one study were generally not well predicted by the model or results from another study. In many cases blend effects were small, on the cusp of statistical significance, and overall blend effects were difficult to quantify. The latest studies on GDI engines found little effect on gaseous emissions, and an increase in PM mass emissions with the addition of ethanol.

The EPAct study model was formulated in log-linear space, and is used in a relative fashion, with a chosen baseline fuel and emissions factor combination. It is frequently used for emissions predictions via the EPA MOVES model. The EPAct model did not describe accurately ethanol effects from fuel pairs in the earlier E-67 program. The model was also applied to proposed real-world fuel properties for E0, E10 and E15. The ethanol coefficient, if used alone, raised NOx and PM emissions, but typical E10 and E15 fuels also enjoy a reduction of aromatics and a reduced value of T50. When aromatic and T50 coefficients were also used in the EPAct model, ethanol addition lowered NOx and PM emissions. Even for splash blending, diluted aromatics and reduced T50 temperature showed EPAct model NOx and PM predictions that changed little with ethanol content. Typically the EPAct model and most studies agree that ethanol is either beneficial or has minimal effect in changing THC and CO emissions.

Differences between study conclusions were attributed to several factors, and these causes erode confidence in overall summary conclusions on the effects of ethanol. Variation in vehicle emissions behavior of the vehicles in a study is noteworthy. Variations in anti-knock properties of the fuel may influence ignition timing strategies in engine operation demanding high torque (as in the US06 cycle), leading to changes in efficiencies and emissions. Inadequate conditioning of vehicles may cause the vehicle to adapt to the fuel during a recorded emissions test.

Emissions levels of late model year vehicles are low and difficult to measure, and studies have used very high difference criteria between two repeat runs to initiate an additional test. This implies that a small study with few runs can offer only approximate or niche conclusions. Larger studies are limited in accuracy when addressing a specific part of their fleets. For the multivariate studies, resource limitations prevent use of full test matrices and multiple repeat runs, eroding statistical confidence.

The blending of fuels used in the studies represents a major cause of differences in conclusions and draws into question applicability to real world predictions. In match blending, it is not possible to add ethanol to a BOB and hold all other properties constant. Blending to match selected properties for multivariate analyses may neglect or embolden other properties that have influence on the emissions, but that are not considered in the model. Some multivariate studies do not employ a fuel descriptor variable that is known to be influential on emissions, so that a major axis is not explored. Blending to match selected properties may not represent real world fuel compositions, confounding the expected physics and chemistry in the engine.

T50 is used in disparate ways, is not readily translated between studies, and is co-dependent on ethanol content. In some cases, the T50 value in a match blend represents a natural value that is lowered by presence of ethanol. In others, the blending is targeted such that T50 is forced to be similar for ethanol and non-ethanol blends, distorting the expected distillation curve. T50 is a critical component in the drivability index but T50 does not serve that task well if it is an ambiguous variable.

Emissions are influenced by both molecular structure and molecular weight, and a variable that reports only one of these properties lacks specificity. Use of T50 and aromatic content separately fails to tell whether the aromatics are heavy, for example, and does not target PM effects. PMI, or a variable that compounds weight and aromaticity, is more informative. Studies adopt different parameters for planning, blending and modeling, stressing a lack of agreement between researchers on root cause of emissions and definition of fuel behavior. Reselection of one parameter may change the attribution of emissions to another parameter, such as ethanol level, shedding light on interdependency of chosen variables.

A study cannot predict effects outside of the study space. Study conclusions are reliable in real world predictions only if the study employs real world fuels or a multivariate study that varies some key parameters within a realistic molecular soup. In the case of in-use ethanol blends, whether current or moot, emissions predictions at constant AKI must take into account the real-world reductions in aromatics that occur due to refinery practice and the lowering of T50 due to blending behavior.

Care must be taken in addressing emissions from mid blends, insofar as the step in properties from E0 to E10 is very different than the step from E10 to E15 or to E20. Linear extrapolation is not possible.

The advent of model-based and fully adaptive engine controls will emphasize an inseparable bond between fuels and engines. GHG concerns will demand mutual optimization of the fuel and engine, and attack the norms for fuel effects studies. This will heighten the difficulty of predicting total emissions effects on the U.S. legacy fleet, which is gaining in average age.

Key Points of Meta-Analysis Below

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Key Points from the Study

- Numerous studies over the last 10 years have looked at the role of ethanol (at 10 vol% and higher blends) in criteria pollutant emissions, particularly nitrogen oxide (NOx) and particulate matter (PM). Major studies, particularly those carried out by U.S. EPA and the Coordinating Research Council (CRC) have highlighted ethanol's potential to raise PM and either raise or maintain NOx. However, the first major study of new gasoline direct injection (GDI) engines did not find that NOx had a statistical increase.

- Over time, these findings have permeated into the public domain creating a perception among consumers and policymakers that ethanol is not beneficial, and is in fact, harmful to air quality (as opposed to GHG emissions). The perception that ethanol may raise PM emissions is particularly damaging considering its designation as a human carcinogen by the World Health Organization (WHO) and governments' increasingly aggressive actions to decrease these emissions, including in transport. Moreover, this negative perception has impacted discussions in raising ethanol blend levels to 15 vol% in the U.S. and to 10 vol% nationwide in countries around the world, such as in Mexico.

- The reality, as shown in this report, is that measured and modeled effects of ethanol blending on gaseous and particulate emissions have varied widely between studies, to the point that it is difficult to reach <u>any summary conclusions</u> on ethanol's emissions effects. Why? For one thing, automotive technology is evolving, especially with the advent of the GDI engine. Vehicles may interact with specific fuels and test cycles in different ways, leading to inconsistent results.

- Another major issue this report discusses in depth is the fuel itself. The blending of fuels used in the studies reviewed represents a major cause of differences in conclusions and draws into question applicability to real-world predictions. This is a major study finding here, and that is something that needs to be highlighted to the affected industries (including the ethanol industry) and policymakers alike.

- Quite simply, many of the blends used in emissions studies <u>do not</u> reflect typical makeup of in-use fuels. They are <u>not</u> reflective of real-world fuel blending that happens at the refinery or terminal. This is certainly the case in studies where "match blended" fuels were used to test a few select parameters, such as ethanol.

- In match blending, it is just not possible to add ethanol to a blendstock for oxygenate blending (BOB) and hold all other properties constant. Matching select properties such as aromatics or T50 requires addition of higher emission aromatic streams which significantly contribute to emissions. The match blending essentially alters the emission characteristics (higher emissions) of the E0 fuel, increasing the emissions of the match blended ethanol blend and misrepresenting study conclusions on the impact of ethanol. Further, the blending of different hydrocarbon groups and the blending of ethanol produces nonlinear property responses, causing added uncertainty.

- Splash blended fuels provide a study fuel closer than match blending to real world fuel blending but ignores any AKI effects on emissions and fails to account for the reduction in fuel aromatics results in real world blending, and its impact on emissions.

- Variability between studies in itself suggests that many studies <u>should not be used</u> to predict real-world emissions effects, and the causes of the variability between studies are also likely to cause differences in emissions effects between most study conclusions and the real-world application.

- Study conclusions are reliable in real-world predictions <u>only</u> if the study employs real-world fuels or is a multivariate study that varies some key parameters within a realistic "molecular soup." Study conclusions are suited to real-world predictions only if the study addresses the fuels of interest <u>holistically</u>. This means all appropriate parameters in a multivariate model derived from the study must be employed. For example, real-world ethanol blends typically have reduced T50 and lower aromatics than an E0, and all three property changes must be considered in using a model to predict PM or NOx.

- Studies adopt different parameters for planning, blending and modeling, stressing a lack of agreement on root cause of emissions. Variation in emissions is assigned to parameters, but those assignments vary between studies. Reselection of one parameter may change the attribution of emissions to another parameter, such as ethanol level. This is important, yet not accounted for, explained or acknowledged in many studies reviewed here.

- Future studies seeking to clarify real world ethanol level effects on emissions, whether multivariate analyses or direct comparisons, should seek to use fuels at different blend levels that are derived from real refinery streams or thoroughly represent real world fuels, without imposing limiting parameters in the blending. They should also consider refinery economics and not blend just high-value streams. Only in this way can the affected industries, consumers and policymakers gain real insight and understanding as to the impact ethanol has on emissions. Suggestions for potential study designs are incorporated in the report.

- Care must be taken in addressing emissions from mid blends, insofar as the step in properties from E0 to E10 is very different than the step from E10 to E15 or to E20. Linear extrapolation is not possible, though some studies have not defined their model limits.