EFFECTS OF E15 ETHANOL BLENDS ON TAILPIPE AND EVAPORATIVE POLLUTANT EMISSIONS IN CALIFORNIA

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EXECUTIVE SUMMARY

This literature review evaluates the available air emissions data to determine the likely impact of increasing the concentration of ethanol from 10% to 15% in fuel for spark ignition vehicles in California. Since only vehicles that have been built since model year (MY) 2001 are permitted to use E15 under EPA regulations, only tests on these more modern vehicles are considered. The dataset considered includes tailpipe emissions from a total of 56 vehicles, including one FFV, of which 20 were tested on E10 and E15. The remaining were tested on either E0 and E15 or E10 and E20 and thus provide an upper bound to the difference in emissions expected from increasing the ethanol content from E10 to E15. A summary is included in Table 1.

None of the studies, whether done on California fuels or other U.S. fuels found a significant difference in NO_x emissions due to changes in ethanol content in the fuel. One study (of E10 vs. E20) found a significant decrease in NMHC emissions, and another study (of E0 vs. E15) found a significant decrease in CO emissions with higher ethanol content. Only seven non-FFVs were tested on fuels intended to represent California specific fuels. These vehicles averaged a statistically insignificant change in NO_x, with a p-value of 0.91, and a small increase in NMHC (+13%, p=0.17) and a slight decrease in CO (-4%, p=0.26), both of which would also be considered statistically insignificant in comparison to the variability between vehicles. The only FFV tested on California E10 and E20 showed a decrease in NO_x, NMHC and CO emissions.

All statistical analyses were conducted on the log transformed data. The DOE Intermediate Fuel Blends study found evidence that newer vehicles are better at adapting to changes in ethanol content than older vehicles due to an improvement in combustion control during wide open throttle. The relatively smaller statistical significance of the change in NO_x emissions in studies using newer vehicles may reflect that change.

TABLE 1. TAILPIPE EMISSIONS STUDIES

Study Name	Test Cycle	No. of Vehicles	Vehicle Model Years	Fuels	NO_x	NMHC	CO
CRC E74B	FTP	11	2001-2006	E10 vs. E20	No significant difference	⬇	No significant difference
DOE Intermediate Fuel Blends	LA-92	13	2001-2007	E10 vs. E15	No significant difference	No significant difference	No significant difference
DOE Catalyst Study	FTP	24	2003-2009	E0 vs. E15	No significant difference	No significant difference	⬇
UC Riverside	UC and FTP	7	2007-2012	E10 vs. E15	No significant difference	No significant difference	No significant difference
UC Riverside	FTP	1 FFV	2007	E10 vs. E20	E20 emissions less than E10	E20 emissions less than E10	E20 emissions less than E10

Evaporative emissions were also considered. Testing has been limited to measurement of permeation emissions, because it is generally assumed that other sources of evaporative emissions, such as liquid leaks, are independent of the composition of the fuel. Vapor system leaks, whether through canister breakthrough or vapor leaks are primarily dependent on vapor pressure. Permeation emissions from E15 have not been tested, but the Coordinating Research Council (CRC) has tested permeation emissions from E10 and E20. No statistically significant difference in emissions could be found between E10 and E20, and some procedures resulted in an average increase in emissions with the higher ethanol content while others resulted in a decrease, suggesting any measured changes were due to chance, measurement error or variability between vehicles.

TABLE 2. PERMEATION EMISSIONS.

Study Name	Test Cycle	Vehicles	Fuel	VOCs
E65-3	Diurnal	4	E10 vs. E20	No significant difference
E77-2	Static Permeation	6	E10 vs. E20	No significant difference
	Running Loss	6	E10 vs. E20	No significant difference
	Hot Soak	6	E10 vs. E20	Average of 57% reduction in emissions but no p value could be calculated because in some cases there were no measurable emissions
	3-Day Diurnal	6	E10 vs. E20	No significant difference

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Introduction

California's Low Carbon Fuel Standard (LCFS), adopted in 2009, and further amended in 2011 requires a ten percent reduction in the greenhouse gas impact (on an energy specific basis) of California's transportation fuels by 2020. In order to reach this goal, the LCFS mandates the providers of transportation fuels to increase the amount of low carbon fuels, such as ethanol, included in the transportation energy mix. In order to provide more pathways for attaining the LCFS, the California Air Resources Board (CARB) may consider allowing the concentration of ethanol in gasoline to rise to 15% (or E15) from 10% (E10), the current limit. While reducing greenhouse gases is a high priority, it is also essential to ensure that fuel changes do not adversely impact local air quality by increasing ozone or other atmospheric pollutants. This review is intended to summarize the expected changes in tailpipe and evaporative emissions of nitrogen oxides (NO_x), organic compounds (whether measured as non-methane hydrocarbons (NMHC), total hydrocarbons (THC), total volatile organic compounds (VOCs) or ozone-forming potential) and carbon monoxide (CO) if the allowable ethanol content were permitted to rise from 10% to 15% in California.

Extensive research has been conducted on the impact of ethanol in gasoline on emissions and emissions control systems of ethanol in gasoline. In the past decade that research has focused on increasing the concentration of ethanol from E10 to E15. Based on those results, the U.S. EPA permitted the use of ethanol containing fuels at concentrations of up 15% in cars as old as model year 2001 as well as all flex-fuel vehicles. This includes more than 75%[1] of the cars, trucks and SUVs on the road today. However, California has not yet permitted this change.

Vehicles

This review is limited to test results from vehicles that are model years 2001 or later, as these will be the only vehicles permitted to use E15 by EPA regulation and represents the vast majority of vehicles on the road. There is some evidence that older vehicles even among those in the post-2001 model years are less effective at adapting to higher ethanol contents quickly, resulting in higher NO_x emissions and lower CO, THC and NMHC emissions. This will be discussed further below.

Flexible fuel vehicles (FFVs) are vehicles designed and permitted to use any ethanol fuel level up to E85, but many may fill up with conventional fuel and so may be impacted by a change in the availability of E15 in place of E10. According to IHS Automotive[2] there are nearly 20 million FFVs on U.S. roads today, or somewhere around one-tenth of the total number of vehicles on the road. Only one has been tested on E15 and E10, and the results of that test are included in this analysis.

Fuels

Fuels sold in California may contain no more than 3.5% oxygen or 10% ethanol, and, in some areas, must contain at least 1.8% oxygen (roughly 5% ethanol). However, virtually all gasoline sold in California contains 10% ethanol and thus, E10 seems the appropriate baseline against which new fuels should be compared.

All ethanol-containing fuels in California must be prepared using petroleum blendstocks for oxygenate blending that meet California's requirements. Acceptable California blendstocks are intended to burn more cleanly than conventional blendstocks used in other parts of the country. In order that petroleum blendstocks can be produced independently of ethanol blending, California has developed a Predictive Model to estimate the emissions effect of changes in the blendstock and ethanol concentrations. The Predictive Model was intended to ensure the finished fuel meets requirements on vapor pressure; the maximum sulfur, benzene, aromatic and olefin content; and certain distillation properties. All of these properties are affected by the addition of ethanol, some just slightly by simple dilution, but others such as vapor pressure and distillation properties change in highly non-linear ways. The Model was not intended to be used for ethanol concentrations of greater than 10%. If E15 were permitted in California, it is not clear exactly how or if the base blendstock would change, but in addition to regulatory requirements it could also be affected by the efforts of petroleum producers to reduce production costs. For example, a higher ethanol content means less need for the potentially more expensive, higher octane components from petroleum.

Of the applicable emissions testing discussed in this paper only one study,[3] by Karavalakis and colleagues at UC Riverside, used a base or test fuel that was specifically described as "CARB" fuel. In that case, the base CARB fuel included 6.6% ethanol and was diluted with small amounts of ethanol to make E10 and E20 and was tested on only one 2001+ vehicle. In other work conducted at UC Riverside [4] the fuel was described as follows:

> "The ethanol fuels were blended …………to represent ethanol fuels that would be utilized in California, in terms of properties such as aromatic content, Reid vapor pressure (RVP), and other properties."

This description implies that these fuels were intended by the researchers to be representative of both the clean burning E10 CARB fuel that is currently in use and the E15 that would be produced in California if it were permitted. Without knowing more about what restrictions will be placed on E15 blendstocks in the future, this is the study which appears most likely to represent the change being considered in California fuel. The UC Riverside work which utilized these fuels included seven standard vehicles (all model year (MY) 2007 or 2012). Thus, while the review will emphasize the work done at UC Riverside on fuels that are specifically designed to be representative of California, other studies done on non-California fuels will also be considered.

When ethanol is added to a petroleum blendstock it typically raises the vapor pressure by about 1 psi, and lowers the T50 (temperature at which 50% of the blend evaporates) and may affect other distillation parameters such as T90. Many of the studies discussed here employed some type of match blending, i.e. when blending fuels, ethanol is not just added to base fuel. Instead other components of the petroleum blendstock were also varied to maintain a constant vapor pressure, and certain other distillation or composition properties. It is likely that if E15 were permitted in California it would be required to meet some or all of the same property standards that E10 currently meets, and thus match blending for those properties would be representative of the expected fuels. However, using the results of match blended fuels to represent future California fuels is complicated by a number of difficulties:

- match blending for multiple properties is difficult and rarely perfectly successful, because it is impossible to change one property without changing many of the other properties;
- despite extensive study it is not clear which fuel properties are most important for emissions because the effects of correlated properties cannot be easily separated from each other by statistical analysis;
- there are numerous properties that could conceivably have an impact on emissions[*] such that no study could be large enough to test every one;
- the way in which California will regulate the properties of higher ethanol content fuels is not yet known;
- refiners will work within new regulations to produce the lowest cost blendstocks that meet new California regulations in ways that are beyond the scope of this document to predict.

Because approaches to match blending can be slightly different, it is not surprising that we see some variability in emissions results due to choices made in the way blending is done and, in addition due to the wide variability between vehicles and base fuels.

[*] See for example, "Analysis of EPAct Emission Data Using T70 as an Additional Predictor of PM emissions from Tier 2 Gasoline Vehicles," (Darlington, T. et al. SAE 2016-01-0996).

Because of the limited number of studies done comparing E15 to E10, this review will also describe tests made which compare E20 to E10, and E15 to E0. Those studies should be considered to provide an upper bound to the emissions changes due to the smaller content change between E15 and E10. Ethanol's impact on fuel properties, particularly vapor pressure, are notably non-linear with a significant bend in the vapor pressure curve at about E10 and a highly variable impact on T50 (the distillation temperature at which 50% of the fuel evaporates) between E10 and E20.

Statistical Analysis

Because test procedures were different, each dataset was analyzed independently. All emissions are presented on a g/mile basis and were transformed logarithmically prior to the statistical analysis to equalize the impact of high and low emitting vehicles in determining statistical significance of changes. Logarithmic transform of data is common with emissions data. Results were considered to be statistically significant for $p<=0.05$ and marginally significant if p fell between 0.05 and 0.1.

Tailpipe Emissions

Non-California Fuel Studies

Coordinating Research Council Study E74-B

The Coordinating Research Council (a consortium of car and petroleum companies) conducted a study[5] in 2009 which included 15 vehicles, model years 1994 to 2006, tested over the Federal Test Procedure (FTP) cycle. The study was intended to separate the effects of vapor pressure, ethanol content and test temperature on CO exhaust emissions, but NMHC and NO_x emissions were also reported. Seven match blended[†] E0, E10 and E20 fuels were tested at several different vapor pressures. Because their study included vehicles older than the 2001 MY cutoff, and E0 fuels, the CRC statistical analysis is not considered directly applicable. Instead, in Table 1, the dataset has been limited to tests conducted on post 2001 MY vehicles, the E20 fuel and the only E10 fuel with the same vapor pressure.

The results showed that for vehicles using both E20 and E10, the higher ethanol content fuel yielded an increase in NO_x in 6 out of the 11 vehicles at 75 °F, and for 7 out of 11 vehicles at 50 °F. The 2006 Ford Taurus seemed to show an especially large sensitivity to ethanol content in both tests. However, when the wide variability between vehicles is taken into account, the change in NO_x is not statistically significant (p=0.18) and could be due to chance alone. Similarly, there was a decrease in NMHC emissions for E20 in 8 out of 11, and 6 out of 11 vehicles in the 75 °F and 50 °F tests respectively. For the 75 °F test, the difference between NMHC emissions using the two different fuels is statistically significant at the 95% level (p <=0.05), but not for the 50 °F test. Finally, for CO, 6 of the 11 vehicles saw a decrease at 75 °F, 7 out of 11 saw a decrease at 50 °F, but, statistically, this difference was not significant at either temperature.

Overall, there is little apparent difference in emissions between E10 and E20 from later model vehicles (2001+) for these criteria pollutants; given that differences between E10 and E15 should be smaller, the impact of changing from E10 to E15 would probably not be detectable in these vehicles.

[†] The fuels were blended to match four distillation points, octane values, and aromatic, benzene, olefin and sulfur content as close as practicable. For the E20 fuel, especially, a tight match was not possible.

TABLE 3. CRC E74-B TAILPIPE EMISSIONS FROM FTP CYCLE AT 75 °F (TOP) AND 50 °F (BOTTOM) USING E10 AND E20

Vehicle No.	NO_x Emissions, g/mi			NMHC Emissions, g/mi			CO Emissions, g/mi		
	E10	E20	Change	E10	E20	Change	E10	E20	Change
2001 Corolla	0.176	0.139	-21%	0.071	0.064	-10%	0.99	1.04	5%
2002 Altima	0.182	0.176	-3%	0.049	0.051	4%	1.94	1.54	-21%
2001 Caravan	0.296	0.506	71%	0.066	0.051	-23%	0.57	0.35	-39%
2002 Trail Blazer	0.182	0.185	2%	0.084	0.058	-31%	0.52	0.44	-15%
2004 Stratus	0.048	0.058	21%	0.036	0.023	-36%	0.36	0.28	-22%
2004 Impala	0.045	0.027	-40%	0.054	0.044	-19%	0.50	0.52	4%
2004 Camry	0.046	0.037	-20%	0.024	0.024	0%	0.15	0.18	20%
2006 Taurus	0.046	0.089	93%	0.030	0.023	-23%	0.23	0.06	-74%
2004 Ram 1500 SLT	0.099	0.110	11%	0.054	0.056	4%	0.68	0.66	-3%
2004 Escape	0.048	0.057	19%	0.037	0.034	-8%	0.20	0.17	-15%
2004 Highlander	0.055	0.050	-9%	0.024	0.026	8%	0.14	0.23	64%
Average			11%			-12%			-9%
p value (two tail) of log transformed values			0.61			0.023			0.25

Vehicle No.	NO_x Emissions, g/mi			NMHC Emissions, g/mi			CO Emissions, g/mi		
	E10	E20	Change	E10	E20	Change	E10	E20	Change
2001 Corolla	0.158	0.136	-14%	0.085	0.111	31%	1.63	1.48	-9%
2002 Altima	0.263	0.278	6%	0.085	0.078	-8%	1.98	1.79	-10%
2001 Caravan	0.42	0.33	-21%	0.078	0.067	-14%	0.59	0.6	2%
2002 Trail Blazer	0.192	0.197	3%	0.089	0.078	-12%	0.55	0.52	-5%
2004 Stratus	0.061	0.087	43%	0.057	0.045	-21%	0.39	0.34	-13%
2004 Impala	0.035	0.035	0%	0.078	0.076	-3%	1.53	1.37	-10%
2004 Camry	0.047	0.052	11%	0.06	0.063	5%	0.2	0.26	30%
2006 Taurus	0.025	0.119	376%	0.046	0.044	-4%	0.47	0.29	-38%
2004 Ram 1500 SLT	0.142	0.114	-20%	0.091	0.091	0%	0.99	0.95	-4%
2004 Escape	0.081	0.119	47%	0.061	0.067	10%	0.4	0.67	68%
2004 Highlander	0.042	0.055	31%	0.033	0.039	18%	0.24	0.28	17%
Average			42%			0%			2%
p value (two tail) of log transformed values			0.23			0.84			0.93
Average of results at both temperatures			27%			-6%			-3%
p value (two tail) of log transformed values of results at both temperatures			0.18			0.051			0.27

The Department of Energy (DOE) Study of Intermediate Blends on Legacy Vehicles

This study[6] included a number of vehicles older than 2001 and therefore the statistical analysis which accompanied the study is not applicable. Instead the data from the 2001+ MY vehicles were extracted and are shown in Table 2. In this case we were able to compare E15 with E10 and found NO_x increased in 7 out of 13 of 2001+ MY vehicles, and NMHC and CO decreased in 7 out of 13 vehicles, and 8 out of 13 vehicles, respectively. In comparison to the variability between the vehicles, the paired t-test conducted for each of these pollutants finds that the difference between the E15 results and the E10 results is not significant.

TABLE 4. DOE INTERMEDIATE BLENDS ON LEGACY VEHICLES TAILPIPE EMISSIONS ON LA-92 CYCLE USING E10 AND E15.

Vehicle	NO_x Emissions, g/mi			NMHC Emissions, g/mi			CO Emissions, g/mi		
	E10	E15	Change	E10	E15	Change	E10	E15	Change
2001 PT Cruiser	0.171	0.171	0%	0.021	0.019	-10%	1.89	1.76	-7%
2003 Le Sabre	0.034	0.042	24%	0.019	0.022	16%	0.25	0.32	28%
2003 F150	0.016	0.016	0%	0.063	0.054	-14%	0.92	0.78	-15%
2003 Taurus	0.078	0.079	1%	0.048	0.042	-13%	0.5	0.41	-18%
2003 Altima	0.042	0.051	21%	0.049	0.072	47%	0.52	0.65	25%
2003 Camry	0.154	0.164	6%	0.048	0.043	-10%	4.95	5.07	2%
2004 Golf GTI	0.042	0.028	-33%	0.018	0.017	-6%	0.53	0.49	-8%
2007 Lucerne	0.058	0.056	-3%	0.034	0.031	-9%	1.86	1.81	-3%
2007 Silverado	0.039	0.035	-10%	0.035	0.039	11%	1.4	1.32	-6%
2007 T&C	0.017	0.034	100%	0.023	0.028	22%	1.02	1.23	21%
2007 F150	0.008	0.012	50%	0.038	0.042	11%	2.21	1.87	-15%
2007 Accord	0.009	0.009	0%	0.01	0.006	-40%	0.18	0.14	-22%
2007 Camry	0.037	0.032	-14%	0.015	0.016	7%	0.13	0.16	23%
Average	0.054	0.056	11%	0.032	0.033	1%	1.26	1.23	0%
p value (two tail) of log transformed values			0.34			0.84			0.84

One interesting result of the study was that while all of the vehicles adapted well to the higher ethanol content fuel for most operating conditions, some vehicles did not adapt well to the higher ethanol content at wide open throttle. This resulted in lean conditions, i.e. excess oxygen in the combustion zone and a noticeable increase in NO_x, coupled with a reduction in CO and NMHC under wide open throttle conditions. This effect was too subtle to create a statistically significant difference in overall emissions in the tested engine cycle but it was detectable when wide open throttle conditions were considered independently. The vehicles that adapted effectively used an engine control unit strategy known as long term fuel trim (LTFT) to avoid excursions into lean operation under wide open throttle conditions. The study authors found that LTFT was more prevalent in the later model vehicles. Should car makers continue to implement this strategy in new vehicles, modern cars will spend more time closer to optimal oxygen levels at all ethanol levels, and thus show an even smaller impact from changing ethanol concentrations.

DOE Catalyst Study

The purpose of this study[7] was to determine if the use of higher ethanol content fuels for the full useful life of a vehicle (as defined in the EPA emissions standards) would adversely affect the emissions control systems and result in emissions which exceeded the EPA emissions standards. Vehicles accumulated mileage on E0, E10, E15 or E20 and then were tested at 3 mileage levels on different ethanol fuels. The vehicles aged on E15 were tested on E15 and E0, and the vehicles aged on E20 were tested on E0 and E20. No vehicles were tested on both E10 and E15 in this program. For the purposes of this analysis, the table below includes only the emissions test results for vehicles tested on both E15 and E0.

TABLE 5. DOE CATALYST STUDY OF TAILPIPE EMISSIONS ON FTP CYCLE USING E0 AND E15 AT FULL USEFUL LIFE.

Vehicle	NO_x Emissions, g/mi			NMHC Emissions, g/mi			CO Emissions, g/mi		
Fuel	E0	E15	Change	E0	E15	Change	E0	E15	Change
2007 Accord	0.016	0.024	50%	0.024	0.0184	-23%	0.24	0.13	-46%
2006 Silverado	0.036	0.035	-3%	0.035	0.0574	64%	0.99	0.76	-23%
2008 Altima	0.051	0.053	4%	0.053	0.0545	3%	0.62	0.62	0%
2008 Taurus	0.009	0.013	44%	0.013	0.0275	112%	0.42	0.45	7%
2007 Caravan	0.036	0.047	31%	0.047	0.0385	-18%	1.56	1.12	-28%
2006 Cobalt	0.026	0.027	4%	0.027	0.0409	51%	0.45	0.47	4%
2007 Caliber	0.059	0.059	0%	0.059	0.0769	30%	4.3	3.61	-16%
2009 Liberty	0.056	0.045	-20%	0.045	0.0448	0%	1.77	1.16	-34%
2009 Explorer	0.031	0.028	-10%	0.028	0.0585	109%	1.18	1.04	-12%
2009 Civic	0.03	0.043	43%	0.043	0.0333	-23%	0.46	0.33	-28%
2009 Corolla	0.056	0.047	-16%	0.047	0.0528	12%	0.6	0.57	-5%
2005 Tundra	0.039	0.035	-10%	0.035	0.0545	56%	1.17	0.94	-20%
2006 Impala	0.038	0.039	3%	0.039	0.0471	21%	1.4	1.44	3%
2005 F150	0.089	0.06	-33%	0.06	0.0901	50%	2.56	2.23	-13%
2006 Quest	0.036	0.04	11%	0.04	0.0694	74%	1.08	1.02	-6%
2009 Outlook	0.022	0.016	-27%	0.016	0.0341	113%	0.62	0.43	-31%
2009 Camry	0.046	0.052	13%	0.052	0.0348	-33%	0.23	0.25	9%
2009 Focus	0.058	0.062	7%	0.062	0.0275	-56%	0.77	0.67	-13%
2009 Odyssey	0.044	0.039	-11%	0.039	0.0278	-29%	0.22	0.2	-9%
2002 Frontier	0.216	0.102	-53%	0.102	0.0933	-9%	3.92	4.02	3%
2002 Durango	0.391	0.462	18%	0.462	0.1523	-67%	2.55	2.34	-8%
2003 Camry	0.118	0.084	-29%	0.084	0.0436	-48%	0.64	0.72	13%
2003 Taurus	0.137	0.155	13%	0.155	0.062	-60%	0.59	0.35	-41%
2003 Cavalier	0.092	0.085	-8%	0.085	0.0608	-28%	0.71	0.56	-21%
Average			1%			13%			-13%
p value (two tail) of log transformed values			0.68			0.93			0.0006

Average emissions in the DOE Catalyst study show significant reductions in CO between E15 and E0, and changes which are not statistically significant in NMOG and NO_x. It is not clear how much of the difference between E0 and E15 occurs between E0 and E10 and what is due to the relatively smaller change between E10 and E15. However, the implication of this study is that changes in emissions, other than a reduction in CO are likely to be non-detectable in these vehicles.

CALIFORNIA STUDIES

A total of seven standard vehicles and one flexible-fuel vehicle MY 2001+, were tested by Karavalakis and his colleagues at UC Riverside using E10 and E15 fuels that would likely be permissible in California should the higher ethanol fuels be legalized. Those results were reported in three different papers[3,4,8] and an extensive statistical analysis of the results from seven of those vehicles was made in a 2015 SAE paper.[4] In addition a single FFV, a 2007 Chevrolet Silverado, will be considered independently of the other vehicles because it is a different type of vehicle and also because it was not tested on E15 but was tested on E20 and E10. Data was provided in a graphic form, and was digitized from a software program called the Web Plot Digitizer.[9] The graphic presentation of the Chevrolet Silverado results was on such a small scale that magnitude could not be accurately gauged and only the direction of change can be reported.

Considering only E15 and E10 emissions from the seven vehicles, Karavalakis and his colleagues found there were no significant differences in the weighted (cold start and running) emissions for THC, NMHC, CO and NO_x emissions, although the cold start emissions were slightly higher for both THC and NMHC for E15, and the difference was statistically significant. They did not report any significant changes in PM mass and total particle number, between E15 and E10. Our analysis, in Table 6 supports these conclusions. The study also reported extensively on other pollutants including methane, carbon dioxide and a number of individual VOCs.

The single FFV (MY 2007) showed small reductions in all pollutants including CO, THC, NMHC and NO_x for E20 in comparison to E10, although none appear statistically significant in comparison to the standard deviations of the measurements as shown on the graph. Tests on higher ethanol concentrations suggest the trend is for reductions in CO, THC and NMHC at E20 and higher ethanol concentrations for this FFV.

Taken together these CARB fuel studies show no evidence for any increase in emissions for CO, THC, NMHC or NO_x if E15 replaces E10 fuel in California.

The total amount and composition of the organics emitted can be analyzed to provide a rough gauge of the ozone-forming potential of the emissions, as not all organics are equally prone to reacting to form ozone. Thus, studies which considered the reactivity of the specific organics released are more accurate at determining the ozone-forming potential of the emissions. The UC Riverside team did this analysis for emissions from two 2012 model year vehicles and found that the ozone reactivity for emissions from E15 was less than those for E10 as shown in the figure below.

TABLE 6. UC RIVERSIDE STUDY OF TAILPIPE EMISSIONS FROM UC AND FTP CYCLES USING E10 AND E15 FUEL

		NO_x Emissions, g/mi			NMHC Emissions, g/mi			CO Emissions, g/mi			THC Emissions, g/mi		
Vehicle	**Test Cycle**	E10	E15	Change	E10	E15	Change	E10	E15	Change	E10	E15	Change
2007 Civic	UC	0.0060	0.0090	50%	0.0173	0.0150	-13%	0.330	0.280	-15%	0.0200	0.0180	-10%
2007 Ram	UC	0.1660	0.1580	-5%	0.0690	0.0700	1%	2.760	2.590	-6%	0.0950	0.0950	0%
2012 Camry	UC	0.0120	0.0100	-17%	0.0035	0.0050	43%	0.030	0.030	0%	0.0050	0.0060	20%
2012 Optima	UC	0.0064	0.0071	12%	0.0065	0.0101	56%	0.124	0.082	-34%	0.0072	0.0103	43%
2012 Impala	UC	0.0071	0.0088	24%	0.0052	0.0059	14%	0.156	0.142	-9%	0.0062	0.0066	6%
2012 Mercedes Benz	UC	0.0257	0.0267	4%	0.0149	0.0114	-24%	0.227	0.184	-19%	0.0220	0.0184	-17%
2012 Mazda 3	UC	0.0109	0.0084	-23%	0.0073	0.0071	-3%	0.631	1.092	73%	0.0079	0.0085	8%
2007 Civic	FTP	0.0097	0.0118	21%	0.0286	0.0260	-9%	0.285	0.253	-11%	0.0315	0.0289	-8%
2007 Ram	FTP	0.0532	0.0473	-11%	0.0071	0.0076	7%	1.487	1.392	-6%	0.0875	0.0919	5%
2012 Camry	FTP	0.0103	0.0087	-16%	0.0039	0.0057	45%	0.025	0.022	-13%	0.0050	0.0059	17%
2012 Optima	FTP	0.0048	0.0051	5%	0.0072	0.0106	46%	0.060	0.070	16%	0.0072	0.0112	55%
2012 Impala	FTP	0.0088	0.0092	5%	0.0057	0.0071	25%	0.161	0.152	-6%	0.0070	0.0085	22%
2012 Mercedes Benz	FTP	0.0087	0.0088	1%	0.0129	0.0097	-25%	0.196	0.177	-10%	0.0160	0.0126	-22%
2012 Mazda 3	FTP	0.0077	0.0064	-17%	0.0072	0.0083	15%	0.576	0.462	-20%	0.0093	0.0101	9%
Average				2%			13%			-4%			9%
p value (two tail) of log transformed values				0.91			0.17			0.26			0.2

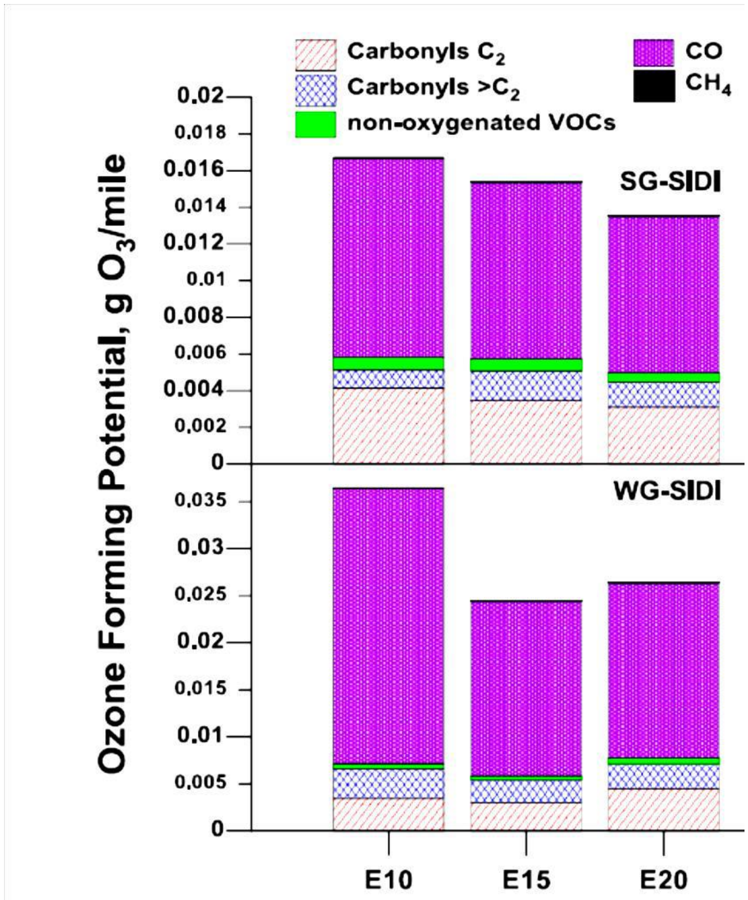

FIGURE 1. OZONE-FORMING POTENTIAL OF TAILPIPE EMISSIONS FROM VEHICLES USING E10, E15 AND E20.[10]

Because of the extremely limited data on the ozone-forming potential of E15 versus E10 the impact of both higher and lower ethanol contents on ozone-forming potential will be briefly mentioned, although this may not be representative of the change between E15 and E10. In their extensive study of flexible fuel vehicle emissions from E6, E32, E59 and E85 fuels the CRC[11] found that the average ozone-forming potential decreased with increasing ethanol content of the fuels on the cold start FTP. There were mixed results on the US06 and Unified Cycle tests. Wang and colleagues[12] in China found a slight improvement in ozone-forming potential calculated from MIR values when E10 was compared to E0 in a Euro 4 vehicle. Taken together, these results suggest that there will be no increase in ozone-forming potential with higher ethanol content fuel.

EVAPORATIVE EMISSIONS

Evaporative emissions are volatile organic compounds which escape from the fuel system of the vehicle. For the past few decades, fuel systems have been constructed to be sealed off from the atmosphere, although emissions can occur due to system liquid leaks, vapor leaks through the air emissions control system and permeation of vapors through the materials that make up the fuel lines and other components of the fuel system.

Liquid leaks are rare but can result in large quantities of emissions. They are due to poorly maintained vehicles, or carelessness when fueling. The composition of the fuel is not believed to have any impact on the amount of liquid leaks.

Because the vapor pressure of fuels is regulated, California E10 and E15 fuels would be expected to have identical vapor pressures. (In many areas of the country E10 is permitted to have a vapor pressure that is 1 psi higher than either E0 or E15 fuel, but it is not expected to be permitted in California). Moreover, the addition of 15% ethanol versus 10% ethanol to a blendstock has an almost identical impact on vapor pressure. Adding an additional 5% ethanol to E10 fuel will change the vapor pressure only minimally as shown in the graph below of tens of different fuels created by mixing 10% ethanol and 15% ethanol in the same blendstock.

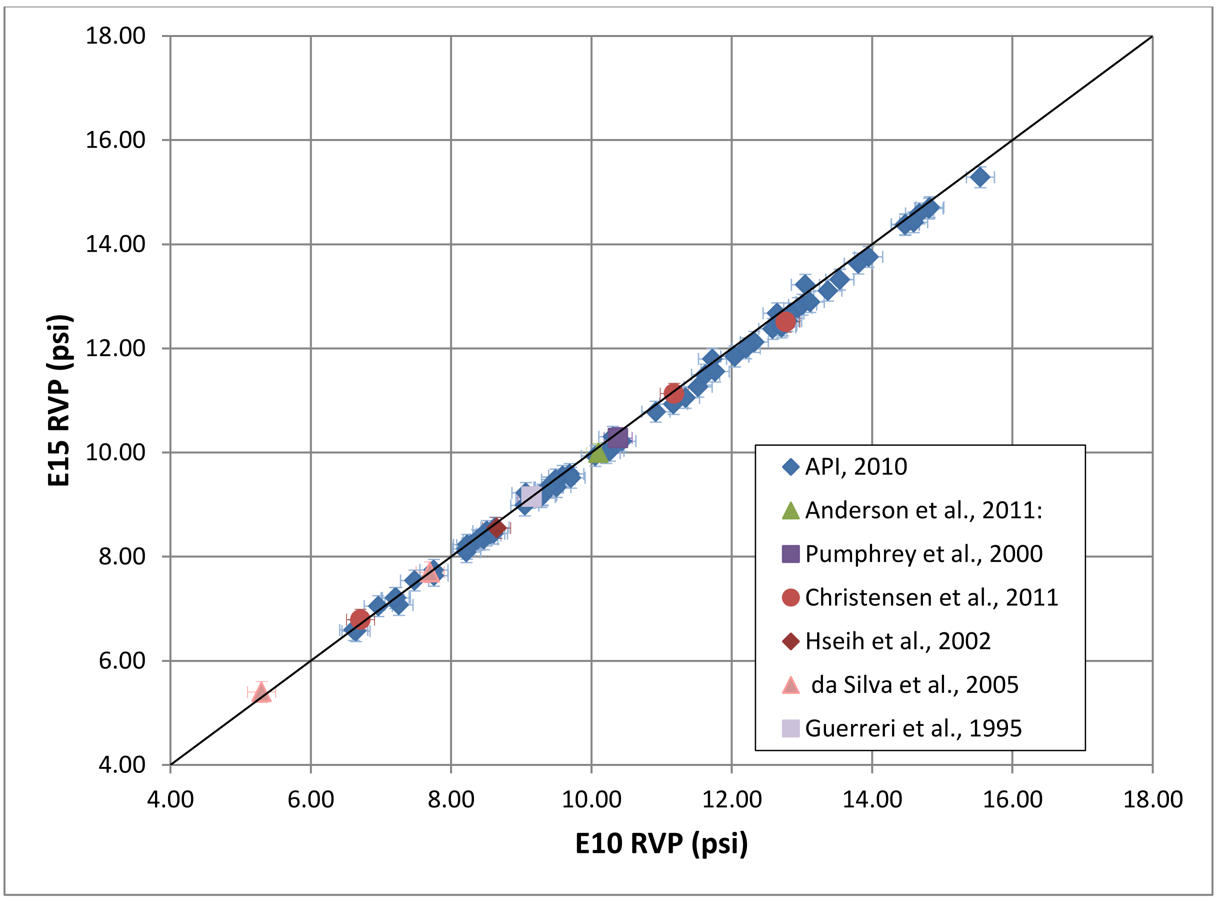

FIGURE 2. VAPOR PRESSURE OF E10 AND E15 FUELS PRODUCED FROM THE SAME BLENDSTOCK.[13]

The quantity of evaporative emissions vented to the emissions control system, and the amount which escapes, would be expected to be roughly the same for fuels with the same vapor pressure. However, permeation emissions, in which fuels move through the fuel system materials are chemical specific and could be different for fuels with different chemical compositions. Two Coordinating Research Council studies were conducted to determine if higher ethanol content would affect permeation emissions.

Coordinating Research Council Study E-65-3

CRC E-65-3[14] was conducted using a number of fuels, and five vehicles, but only the results of E10 and E20 conducted on the four post 2001 MY vehicles are reported below. E15 was not tested. The fuel systems were removed from the vehicles and the fuel rigs were tested over the 24-hour diurnal test in a Variable Temperature Sealed Housing Evaporative Determination (VT-SHED) using the California Enhanced Evaporative Testing rules. Test results in mg/day for the four vehicles are shown in Table 3. Two of the vehicles showed increases comparing E20 to E10, and two showed decreases, and the net change is not considered statistically significant. The specific reactivity of the emissions was measured and the ozone-forming potential was calculated. The result, in Table 8, shows that the ozone-forming potential of the permeation emissions from the two fuels were not statistically distinguishable.

TABLE 7. CRC E65-3 DIURNAL VOC PERMEATION EMISSIONS (MG/DAY)

Vehicle	E10	E20	Change
2001 Tacoma	468	508	9%
2004 Taurus	123	102	-17%
2004 Sebring	64	75	17%
2005 Tahoe	466	360	-23%
average	280	261	-4%
p value (two tail) of log transformed values			0.65

TABLE 8. OZONE-FORMING POTENTIAL OF DIURNAL VOC PERMEATION EMISSIONS (OZONE G/DAY)

Vehicle	E10	E20	Change
2001 Tacoma	1.42	1.63	15%
2004 Taurus	0.29	0.24	-15%
2004 Sebring	0.18	0.22	20%
2005 Tahoe	1.42	1.21	-15%
average			1.3%
p value (two tail) of log transformed values			0.999

Coordinating Research Council Study E-77-2

Similar permeation testing was conducted by Coordinating Research Council[15] in 2010 on six vehicles that were 2001+ MY. Again, the testing was conducted in a SHED to capture permeation emissions, with all of the emissions from the vehicle's activated carbon canister vented to the outside. The vehicles were tested on two E10 fuels, with vapor pressures of 7 psi and 10 psi, and a single E20 fuel with a nominal vapor pressure of 9 psi, but which actually had a vapor pressure of 8.5 psi. In order to equalize any impact of vapor pressure, the emissions results of the two E10 fuels were averaged to roughly estimate the emissions of an 8.5 psi fuel. Measurements were made for the following tests:

- Static permeation: fuel system pressurized and monitored for vapor and fuel leaks at 86 °F
- Running loss: two cycles of the LA-92 test at 86 °F
- Hot soak: one hour immediately following LA-92 test
- Diurnal test: California 3-day test, in which temperature is varied between 65 °F and 105 °F.

	Static Permeation					Running Loss Permeation				
	E10 7 psi	E10 7 psi	E10 7 psi	E10 7 psi	Change btw average E10 and E20	E10 7 psi	E10 10 psi	Average of 7 and 10 psi E10	E20 8.5 psi	Change btw average E10 and E20
2001 Corolla	59.6	41.6	50.6	46.2	-9%	232.8	191.6	212.2	169.7	-20%
2001 Caravan	64.4	78.7	71.6	88.2	23%	812.2	858.1	835.2	1028.2	23%
2004 Escape	23.9	24.4	24.2	16.8	-30%	105.7	133.1	119.4	139.4	17%
2004 Highlander	12.2	10.4	11.3	19.3	71%	97.9	71.9	84.9	102.5	21%
2004 Camry	9.4	19.9	14.7	55.8	281%	56.3	138.3	97.3	410.6	322%
2006 Taurus	21.8	10.6	16.2	4.7	-71%	201.2	148.9	175.1	116.8	-33%
Average					44%					55%
p value (two tail) of log transformed values					0.86					0.43

	Hot Soak Permeation					Diurnal Permeation (3-day)				
	E10 7 psi	E10 7 psi	E10 7 psi	Average of 7 and 10 psi E10	Change btw average E10 and E20	E10 7 psi	E10 10 psi	Average of 7 and 10 psi E10	E20 8.5 psi	Change btw average E10 and E20
2001 Corolla	71.9	29.5	50.7	60.3	19%	5022.3	5266.7	5144.5	5145.4	0%
2001 Caravan	122.2	237.7	180.0	0	-100%	2722.1	3894.5	3308.3	4278.7	29%
2004 Escape	32.9	57.4	45.2	56	24%	1316	12705.2	7010.6	1662.7	-76%
2004 Highlander	0	1.6	0.8	0	-100%	723.9	816.4	770.15	1282.2	66%
2004 Camry	13.8	0	6.9	0	-100%	611.9	781.7	696.8	709.2	2%
2006 Taurus	0	0	0.0	4.9	NA	360.8	315	337.9	289.3	-14%
Average			47.3	20.2	-57%[3]			2878.0	2227.9	+1%
p value (two tail) of log transformed values					0.86					0.65

None of the tests resulted in a statistically significant difference between the average of the E10 7 and 10 psi fuel results and the E20 8.5 psi fuel. Two of the tests showed an average increase in the higher ethanol content fuel, one showed almost no change, and one found a decrease.

Taken together, these results suggest that there is no trend in permeation emissions between E10 and E20. There is no data specific to permeation emissions from E15 fuel, but these results suggest that they will not be significantly different than E10 emissions.

[3] Normally this percentage is calculated as the average of the column above, but it is not possible when there is a datapoint in which the base fuel emissions are 0. Instead in this case percentage change was calculated from the average emissions for each fuel.

CONCLUSIONS AND RECOMMENDATIONS FOR ADDITIONAL RESEARCH

Based on the available data there is no consistent, measurable difference between E10 and E15 tailpipe emissions of NO_x, NMHC or CO, when using either a California-specific base fuel or an EPA-specific base fuel. There is limited evidence that the organics emitted from the tailpipe will have a lower ozone forming potential with E15 in comparison to E10 for both California-specific fuels and other test fuels in the US and China. The total mass of permeation emissions and the ozone-forming potential of those emissions from E20 and E10 are statistically indistinguishable, suggesting that the use of E15 in place of E10 will have no impact on permeation emissions. These results are supported by tailpipe emissions data from 56 vehicles and permeation emissions data from 10 vehicles.

There is a wide variance in the results from different vehicles with some evidence that more modern vehicles may be able to better adapt to higher ethanol content fuels at wide open throttle and this may be evidenced by the relatively smaller statistical significance of the change in NO_x emissions in studies using newer vehicles. Future work should focus on determining the relative prevalence of vehicles which are more successful at adapting to changing oxygen content in the fuel, and considering how changes in vehicle technology and the ongoing modernization of the on-road fleet may impact the emissions from the on-road fleet. The ozone-forming potential of E15 and E10 evaporative emissions from sources other than permeation should be measured and compared.

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[14] CRC E65-3 Fuel Permeation from Automotive Systems: E0, E6, E10, E20 AND E85, Final Report, December, 2006.

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