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Avoided Mortalities from the Substitution of Ethanol for Aromatics in Gasoline with a Focus on Secondary Particulate Formation

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In a previously released paper by this author titled "Cancer Reductions from the Use of High-Octane Ethanol-Blended Gasoline with a Focus on Toxic Air Compounds" we looked at selected toxic air compounds which are known to be carcinogenic and known to be reduced with ethanol blending into gasoline. The selected compounds were either in the volatile or particulate phase and mostly directly emitted from the tailpipe of vehicles. In the present examination we focus on avoided mortalities from the substitution of ethanol for aromatics in gasoline with a focus on secondary particulate formation (see Appendix A for a primer on direct and secondary PM emissions).

The following analysis is principally based on two reports: A publication by authors from the Harvard Risk Center co-authored with the US EPA and EPA's Fuels Trend Report.

The first paper which is coauthored with US EPA (Stackelberg et al.) describes that secondary organic aerosols (SOAs) are a major contributor to PM2.5 with aromatics in gasoline being in turn the most effective precursors to SOAs:[1]

> "Field studies suggest 10% - 60% of fine particulate matter (PM2.5) is comprised of organic compounds. This material may be directly emitted to the atmosphere (primary) or formed from the gas-phase oxidation of hydrocarbon molecules and subsequent absorption into the condensed phase (secondary). The latter portion, referred to as **secondary organic aerosol (SOA), is a major contributor to the PM2.5.** Evidence is growing that **aromatics in gasoline exhaust are among the most efficient secondary organic matter precursors.** While the relative abundance of primary and secondary organic matter is the subject of ongoing debate, air quality models are continually updated to keep up with the latest scientific knowledge […]. In the United States, gasoline-powered vehicles are the largest source of aromatic hydrocarbons to the atmosphere."

Stackelberg et al. also suggest:

> "In the United States, gasoline-powered vehicles are the largest source of aromatic hydrocarbons to the atmosphere. Most gasoline formulations consist of approximately 20% aromatic hydrocarbons, which are used in place of lead to boost octane. Therefore, it has been

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[1] Public health impacts of secondary particulate formation from aromatic hydrocarbons in gasoline; Katherine von Stackelberg, Jonathan Buonocore, Prakash V Bhave & Joel A Schwartz Environmental Health Volume 12, Article number: 19 (2013) https://ehjournal.biomedcentral.com/articles/10.1186/1476-069X-12-19#Tab5

suggested that **removal of aromatics could reduce SOA concentrations and yield a substantial public health benefit**."

The importance of aromatics to secondary PM2.5 formation is corroborated in a report prepared for the Federal Highway Administration.[2] Since a reduction in aromatics will lead to a reduction in SOA we look to the EPA Fuel Trends Report (released in November 2017) which shows the decrease in aromatics from the year 2000 was commensurate with an increase in ethanol blending (see Appendix B).[3] On page 8 that report states: "Ethanol's high octane value has also allowed refiners to significantly reduce the aromatic content of the gasoline, a trend borne out in the data."

In their paper Stackelberg et al. use a) the EPA SPECIATE and National Emissions Inventory databases to estimate the nationwide proportion of aromatic VOCs attributable to emissions from gasoline vehicles (see Appendix C) and then b) the BenMap Model to quantify the health impact associated with exposures to the change in PM2.5 concentrations attributable to aromatic hydrocarbons. The results show 6,330 premature mortalities (upper range) from exposure to aromatic SOA in gasoline emissions.

The source-by-source breakdown of all aromatic hydrocarbon emissions is provided in the Additional File of the Stackelberg et al. paper: Gasoline-related aromatics emissions (Baseline Year 2005) totaled 2.47 million tons which are shown in that paper to result in 6,330 mortalities from exposure to PM2.5 originating from aromatics. From the EPA Fuel Trends Report we can correlate these emissions in tons and the mortalities with the average aromatics content in fuel for that year of 24.5% (Appendix B). If we assume a linear relationship between aromatics removal and a reduction in premature mortalities then we can calculate that the reduced aromatics from ethanol blending (as stated in the Fuel Trends Report) in 2016 will have resulted in proportionally lower mortalities of 4,986 incidents (see table below).

Table 1: Linear Regression Relating Mortalities to Aromatics Content

	Aromatics vol%	**Ethanol vol%**	**Aromatic VOC (ton/year)**	**Mortalities (upper bound)**	**Monetary Damages**
2005	24.5	2.23	2,469,970	6,330	$ 57,603,000,000
2016	19.3	9.57	1,945,731.22	4,986	$ 45,377,057,143
			Difference	**1,344**	**$ 12,225,942,857**

Multiplying the reduction in mortalities from reduced exposure to PM2.5 originating from aromatic hydrocarbons in gasoline by the value of a statistical life of $9.1 million (which measures the willingness to pay to reduce the risk of death) we derive total reduced monetary damages attributable to increased

[2] "The formation of PM2.5 from VOC Precursors is caused when volatile organic gases in secondary organic aerosol (SOA) are oxidized by species such as the hydroxyl radical (OH), ozone (O3), and nitrate (NO3). After oxidation of the VOC, some of the oxidation products have low volatilities and condense on available particles becoming part of the PM. VOCs from the **aromatic group** are the most significant contributor to SOA from anthropogenic sources." Source: William Hodan and Willliam Barnard. "Evaluating the Contribution of M2.5 Precursor Gases and Re-entrained Road Emissions to Mobile Source PM2.5 Particulate Matter Emissions".

[3] Fuel Trends Report: Gasoline 2006 - 2016 ; Office of Transportation and Air Quality; U.S. Environmental Protection Agency; EPA-420-R-17-005; October 2017; https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P100T5J6.pdf

ethanol blending of $12.2 billion. [4;5] We can also calculate that **each one percent by vol. reduction in aromatics saves 258 mortalities from reduced exposure to PM2.5 originating from aromatic hydrocarbons in gasoline and $2.35 billion avoided monetary damages**.[6]

A report by NREL details the aromatics content of several ethanol blended fuels. [7] Table 2 in that report shows that flex fuels (E83) have aromatic contents below 2% which would constitute a reduction of 17% points over the 2016 aromatics content of fuels of 19.3%. Therefore, widespread flex fuel adoption would result in a reduction in 4,470 mortalities from reduced exposure to PM2.5 originating from aromatic hydrocarbons in gasoline and $41 billion in avoided monetary damages. The NREL report also lists several E51 fuels at 6% aromatics content which would reduce mortalities by 3,440 incidents or 31 billion in avoided monetary damages.

Moreover, with this approach we can project the mortality/damages benefits that a new blend with aromatics limits could produce. An E25/E30 with 10% aromatics limits, for example, would result in avoided damages of $22 billion whereas an E25/E30 blend with 15% aromatics limits would result in $10 billion in avoided damages from reduced exposure to PM2.5 originating from aromatic hydrocarbons in gasoline.

Table 2: Avoided Mortalities and Monetary Damages for Different Ethanol Blend Levels

	Aromatics Content (%)	Aromatics Reduction (%)	Reduction in Mortalities	Avoided Monetary Damages
E83	2	17.3	4,469.76	$40,674,771,429
E51	6	13.3	3,436.29	$31,270,200,000
Assumed E25/E30	10	9.3	2,402.82	$21,865,628,571
Assumed E25/E30	15	4.3	1,110.98	$10,109,914,286

Importantly, one must keep in mind that ethanol has other emissions benefits including a reduction in direct PM2.5 emissions.[8;9;10] In fact, the Honda PM Index developed by Aikawa and Jetter predicts PM formation in vehicle exhaust is correlated with the number of double bonds in gasoline hydrocarbons:

[4] Technical Support Document. Estimating the Benefits per Ton of Reducing PM2.5 Precursors from 17 Sector. US EPA Office of Air and Radiation, 2013.

[5] Guidelines for Preparing Economic Analyses; updated May 2014; National Center for Environmental Economics; U.S. Environmental Protection Agency https://www.epa.gov/sites/production/files/2017-08/documents/ee-0568-50.pdf

[6] (6330-4987)/(24.5-19.3)

[7] Property Analysis of Ethanol−Natural Gasoline−BOB Blends to Make Flex Fuel Alleman, Yanowitz; NREL Report, 2016. https://www.nrel.gov/docs/fy17osti/67243.pdf

[8] Jin, D., Choi, K., Myung, C.L., Lim, Y., Lee, Y., Park, S., 2017. The impact of various ethanol-gasoline blends on particulates and unregulated gaseous emissions characteristics from a spark ignition direct injection (SIDI) passenger vehicle. Fuel. http:// dx.doi.org/10.1016/j.fuel.2017.08.063.

[9] Storey, J. M., Barone, T., Norman, K., and Lewis, S. 2010. Ethanol Blend Effects on Direct Injection Spark-Ignition Gasoline Vehicle Particulate Matter Emissions. SAE Technical Paper No. 2010-01-2129. SAE, Warrendale, PA.

[10] Martini, G., Astorga, C., Adam, T., Farfaletti, A., Manfredi, U., Montero, L., Krasenbrink, A., Larsen, B. and De Santi, G. Effect of Fuel Ethanol Content on Exhaust Emissions of a Flexible Fuel Vehicle, JRC Report 2009

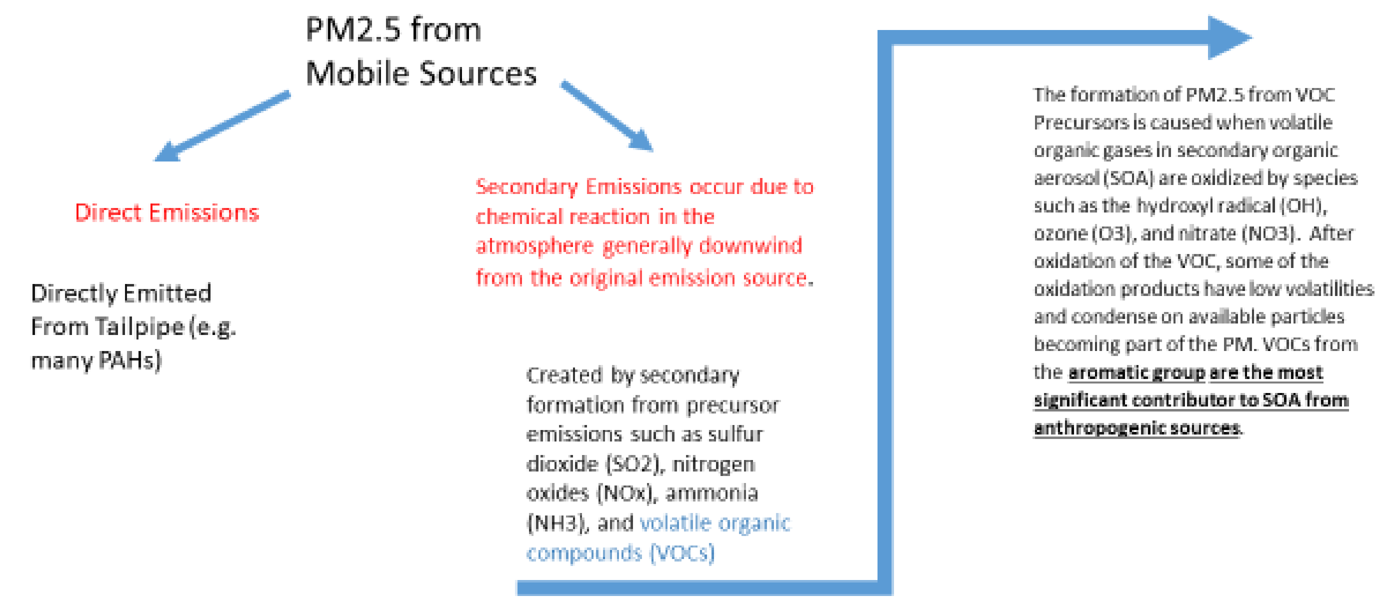
higher distillation aromatics (high molecular weight) have higher double-bond equivalents and therefore contribute directly to PM formation in exhaust emissions whereas ethanol has no double bonds.[11;12]

Also, not all health outcomes were considered in this analysis. As Stackelberg et al state: ”SOA from aromatics in gasoline are associated with other health outcomes, including exacerbation of asthma, upper respiratory symptoms, lost work days, and hospital emergency room visits.”

There are currently no federal limits on aromatics content in gasoline except for benzene which is regulated.[13] Based on the significant mortalities associated with aromatics in gasoline we encourage the development of incentives or regulatory frameworks to reduce aromatics in our fuels.

[11] https://www.sae.org/publications/technical-papers/content/2010-01-2115/
[12] K. Aikawa and J. J. Jetter, "Impact of gasoline composition on particulate matter emissions from a direct-injection gasoline engine: Applicability of the particulate matter index," International Journal of Engine Research, vol. 15, no. 3, pp. 298-306, 24 June 2013.
[13] https://www.epa.gov/gasoline-standards/gasoline-mobile-source-air-toxics

Appendix A: Direct and Secondary PM2.5 Emissions Primer Diagram



Toxic air pollutants, toxic air compounds or air toxics, are those pollutants that are known or suspected to cause cancer or other serious health effects. Toxic Air Compounds is a different classification altogether and are not limited to the particulate phase. Toxics can come out of 4 categories: 1) Volatile Organic Compounds (VOC), 2) Polycyclic aromatic hydrocarbons (PAHs), 3) Dioxins and furans and 4) Metals. Many toxic air compounds can be both in the gas phase and in the particulate phase of vehicle exhaust or condense into the PM phase.

Appendix B: Table from EPA Fuel Trends Report

Year	Volume	Oxygen	API Gravity	Ethanol	MTBE	TAME	Sulfur	Aromatics	Olefins	Benzene	RVP	E200	E300	T50	T90
	Million Gallons	Wt%		Vol%	Vol%	Vol%	ppm	Vol%	Vol%	Vol%	Psi	Vol%	Vol%	F	F
1997	107,220	0.72	60.0	0.31	2.89	0.22	312.6	24.7	12.2	1.01	10.34	49.3	82.5	201.5	331.4
1998	112,950	1.05	60.0	0.80	3.65	0.36	272.7	24.8	11.2	1.00	10.35	49.0	82.6	202.0	329.5
1999	114,776	1.08	60.0	0.97	3.45	0.29	283.8	24.8	11.5	1.00	10.33	49.1	82.6	201.9	330.2
2000	115,574	1.07	60.0	1.07	3.27	0.35	270.2	24.6	11.7	0.99	10.23	49.2	83.0	201.7	327.8
2001	117,153	1.07	59.6	1.05	3.36	0.37	264.1	24.9	12.5	1.02	10.17	48.9	83.0	203.5	327.9
2002	120,802	1.08	59.8	1.14	3.27	0.39	259.4	24.7	11.7	0.97	10.16	48.9	82.8	203.5	329.1
2003	121,617	1.17	59.4	1.33	3.43	0.30	243.8	24.7	11.6	1.00	10.20	49.0	82.6	202.8	330.6
2004	122,166	1.39	60.1	2.02	3.35	0.24	112.0	24.5	11.3	0.98	10.21	49.3	82.7	202.3	330.0
2005	119,666	1.38	60.3	2.23	2.89	0.23	94.8	24.5	11.7	1.04	10.18	49.7	83.4	201.2	326.9
2006	123,178	1.19	60.1	2.91	0.64	<0.01	49.2	24.7	11.1	1.04	10.15	49.1	83.7	-	-
2007	122,403	1.27	60.2	3.44	0.02	<0.01	39.9	24.4	11.2	1.04	10.20	49.6	83.8	-	-
2008	114,032	2.02	60.8	5.54	<0.01	<0.01	34.2	22.5	10.5	1.02	10.33	52.0	85.8	-	-
2009	115,404	2.62	60.3	7.20	<0.01	<0.01	33.3	22.0	10.3	0.97	10.47	52.7	84.8	-	-
2010	116,286	3.13	60.4	8.65	<0.01	<0.01	32.4	21.2	10.0	0.89	10.54	53.8	85.3	-	-
2011	121,131	3.13	60.7	8.72	<0.01	<0.01	30.0	20.2	9.8	0.70	10.64	54.7	86.0	-	-
2012	119,696	3.24	61.0	9.01	<0.01	<0.01	29.4	19.6	9.6	0.63	10.73	55.2	86.3	-	-
2013	119,689	3.33	61.3	9.21	<0.01	<0.01	27.2	19.1	9.5	0.59	10.82	55.7	86.9	-	-
2014	123,005	3.34	61.4	9.23	<0.01	<0.01	25.3	18.8	9.3	0.59	10.95	55.6	87.0	-	-
2015	125,386	3.43	-	9.38	<0.01	<0.01	23.4	19.0	9.0	0.58	10.83	55.0	86.6	-	-
2016	125,000	3.48	-	9.57	<0.01	<0.01	23.1	19.3	8.6	0.58	10.60	54.4	85.9	-	-

Table 6 Summary of Annual Average Gasoline Properties Between 1997 and 2016

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Appendix C: Extracted from Table S2 in Stackelberg et al. - US EPA's SPECIATE Database Used to Determine the Fraction of Anthropogenic SOA from Aromatic Hydrocarbons in Gasoline

tons/year

	Mobile Sources;Highway Vehicles - Gasoline	Mobile Sources;Pleasure Craft	Mobile Sources;Off-highway Vehicle Gasoline, 4-Stroke	Mobile Sources;Off-highway Vehicle Gasoline, 2-Stroke
Aromatic VOC (ton/yr)	1,152,197	688,831	316,224	312,718
Toluene	401,877	219,848	106,474	99,571
M & p-xylene	219,739	126,730	58,810	57,337
Benzene	154,044	99,087	44,259	45,135
Isomers of xylene	0	0	0	0
Ethylbenzene	86,959	48,721	22,809	21,969
O-xylene	82,018	49,019	22,343	22,220
1-Methyl-3-ethylbenzene (3-Ethyltoluene)	59,118	38,254	16,769	17,417
1,2,4-trimethylbenzene (1,3,4-trimethylbenzene)	52,962	32,798	14,716	14,905
1,3,5-trimethylbenzene	22,856	17,116	7,035	7,854
1-Methyl-4-ethylbenzene	24,276	16,980	7,161	7,756
1-Methyl-2-ethylbenzene	16,859	13,868	5,478	6,392
N-propylbenzene	13,888	10,961	4,419	5,046
Benzaldehyde	9,885	9,774	3,574	4,505
Ethylene glycol	0	0	0	0
Phenol (carbolic acid)	0	0	0	0
1,2,3-trimethylbenzene	7,715	5,677	2,377	2,611