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Research Update

PM2.5 Reductions from Ethanol Blends in Gasoline in the Context of the recent COVID-19 death rate link to pollution.

April 28, 2020

Steffen Mueller, PhD. The University of Illinois at Chicago Energy Resources Center

Over the last weeks two papers, one by Harvard researchers and the other one by Italian researchers (published in Environmental Pollution) have linked atmospheric pollution and specifically particulate matter (that have a diameter of less than 2.5 micrometers) as a multiplier of COVID-19 related deaths.[1,2] Specifically, the Harvard study states: "a small increase in long-term exposure to PM2.5 leads to a large increase in COVID-19 death rate, with the magnitude of increase 20 times that observed for PM2.5 and allcause mortality." This creates an additional urgency to rapidly reduce releases of PM2.5 to the atmosphere. In the light of these new developments I have attached two research reports written last summer by the University of Illinois at Chicago Energy Resources Center and collaborators that show how ethanol blended into gasoline will reduce particulate emissions and specifically particulate emissions at the PM2.5 level.

Report 1: This report details the mortalities that have been avoided by blending ethanol into gasoline since ethanol's high octane value has also allowed refiners to significantly reduce the aromatic content of the finished fuel. Aromatics in gasoline exhaust have been shown to be a major contributor to PM2.5. In this report we state that "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."

Report 2: In this study we focus on the mortalities associated with specific toxic air compounds including a series of compounds that are a subset of aromatics which are called polycyclic aromatic hydrocarbons (PAH). The study uses atmospheric models parameterized for the Chicago area. The study shows how ethanol in high octane fuels can reduce the mortalities associated with toxic air compounds via substitution in high-octane gasoline blends. Methodologically, the study follows an EPA developed case study of the benefits of the Clean Air Act on benzene emissions in the Houston area but with newly developed, updated models. These updates include a PAH analysis of vehicle emissions test filters at The Hormel Institute, University of Minnesota, a collaborator in this report.

In the light of the developments that PM2.5 acts as a multiplier (20 times) to all cause mortalities from COVID-19 related deaths the mortality rates from PM2.5 in our reports appear to be grossly underestimated. Consequently, the mortality reductions that can be achieved from higher ethanol blends will likely be a multitude higher than originally calculated.

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[1] Edoardo Conticini, Bruno Frediani, Dario Caro; "Can atmospheric pollution be considered a co-factor in extremely high level of SARS-CoV-2 lethality in Northern Italy?" Environmental Pollution, 2020, ISSN 0269-7491, https://doi.org/10.1016/j.envpol.2020.114465.

[2] Xiao Wu MS, Rachel C. Nethery PhD, M. Benjamin Sabath MA, Danielle Braun PhD, Francesca Dominici PhD; "Exposure to air pollution and COVID-19 mortality in the United States" (Updated April 5, 2020)
All authors are part of the Department of Biostatistics, Harvard T.H. Chan School of Public Health, Boston, MA, 02115, USA

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

Prepared by: Steffen Mueller, PhD, Principal Economist, University of Illinois at Chicago Energy Resources Center

August 2019

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:[3]

> "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 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.[4] Since a reduction in aromatics will lead to a reduction in SOA we look

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[3] 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

[4] "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".

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).[5] 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 ethanol blending of $12.2 billion. [6;7] 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**.[8]

A report by NREL details the aromatics content of several ethanol blended fuels. [9] Table 2 in that report shows that flex fuels (E83) have aromatic contents below 2% which would constitute a reduction of 17%

[5] 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
[6] Technical Support Document. Estimating the Benefits per Ton of Reducing PM2.5 Precursors from 17 Sector. US EPA Office of Air and Radiation, 2013.
[7]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
[8] (6330-4987)/(24.5-19.3)
[9] 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

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

1	2 Aromatics Content (%)	3 Aromatics Reduction (%)	4 Reduction in Mortalities	5 Avoided Monetary Damages
6 E83	7 2	8 17.3	9 4,469.76	10 29 $40,674,771,4
11 E51	12 6	13 13.3	14 3,436.29	15 00 $31,270,200,0
16 Assumed E25/E30	17 10	18 9.3	19 2,402.82	20 71 $21,865,628,5
21 Assumed E25/E30	22 15	23 4.3	24 1,110.98	25 86 $10,109,914,2

Importantly, one must keep in mind that ethanol has other emissions benefits including a reduction in direct PM2.5 emissions.[10;11;12] 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: 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.[13;14]

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.”

[10] 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.
[11] 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.
[12] 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
[13] https://www.sae.org/publications/technical-papers/content/2010-01-2115/
[14] 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.

There are currently no federal limits on aromatics content in gasoline except for benzene which is regulated.[15] 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.

[15] https://www.epa.gov/gasoline-standards/gasoline-mobile-source-air-toxics

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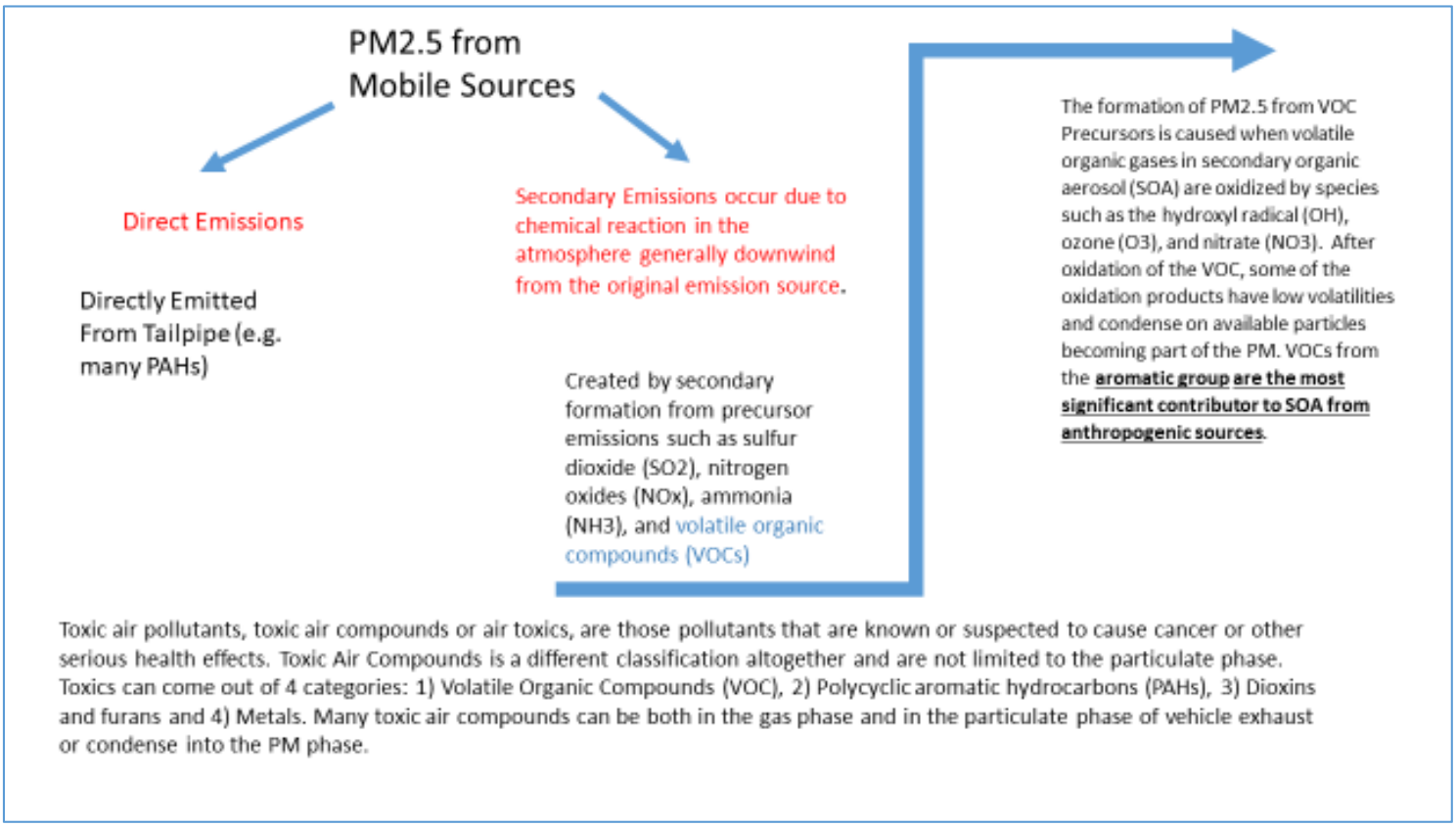
Appendix A: Direct and Secondary PM2.5 Emissions Primer Diagram



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

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

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Cancer Reductions from the Use of High-Octane Ethanol-Blended Gasoline with a Focus on Toxic Air Compounds

Prepared by: Steffen Mueller, PhD, Principal Economist, University of Illinois at Chicago Energy Resources Center

Prepared for: National Corn Growers Association

August 2019

This Study was conducted with substantial in-kind support from The Hormel Institute (THI), The University of Minnesota (UMN), and Oak Ridge National Laboratory (ORNL). ORNL supplied particulate filters from prior fuel economy and emissions tests to THI. THI prepared the samples for further analysis in the UMN gas chromatograph/mass spectrometer. O'Shea Environmental conducted the MOVES2014b and Atmospheric Dispersion Modeling.

Funding was provided by The Hormel Foundation, the National Corn Growers Association, the Illinois Corn Marketing Board, and the Indiana Corn Marketing Board.

We want to thank Gail Dennison, Dr. Zigang Dong, Dr. Srinivasa Reddy, Brian West and his team, Rick Schwarck, Dave Loos, Peter Villa, and William O'Shea and his team.

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Summary

This study lead by the University of Illinois at Chicago Energy Resources Center assesses the cancer reductions from the use of high-octane ethanol-blended gasoline with a focus on toxic air compounds. The present study follows a case study published by the United States Environmental Protection Agency (EPA) in 2011 for benzene-related cancer reductions resulting from the Clean Air Act, albeit with an updated model structure. The focus on toxic air compounds is based on the well-documented substitution and dilution effect of ethanol when blended with gasoline.

We combine pollutant vehicle emissions factor data for gasoline without ethanol (E0) from the MOVES2014b model which was parameterized for the local Chicago area with EPA's CAL3QHC air quality model to predict pollutant concentrations near highways. The resulting toxic air compound concentrations are further adjusted to reflect emissions reductions for high-octane fuels blended with twenty-five percent ethanol (E25).

The emissions factors used in this adjustment were developed from the scientific literature but also from recent vehicle tests conducted by Oak Ridge National Laboratory (ORNL): We obtained the particulate filters from these vehicle emissions tests at ORNL and collaborated with the The Hormel Institute-University of Minnesota-Mayo Clinic (THI) to analyze them in their gas chromatography/mass spectrometry unit. This closed a thin data gap in the scientific literature for a subset of air toxins called polycyclic aromatic hydrocarbons (PAHs). The toxic air compound concentrations reductions document for E25 in this effort where applied to the concentrations for E0 and then converted into a reduction in cancer cases using inhalation unit risk factors. Applying published values of a statistical life resulted in total avoided monetary damages.

Using data from this limited geographic area the study attempts to estimate an upper bound of cancer-related mortality impacts from toxic air compounds on a national level. Given the thin datasets on high octane fuel vehicle emissions studies and modeling limitations this number serves as an approximation of the air toxins health impacts from the use of high octane E25 fuels with clearly understood uncertainties. Besides cancer-related mortalities, toxic air compounds also have morbidity impacts which are not quantified.

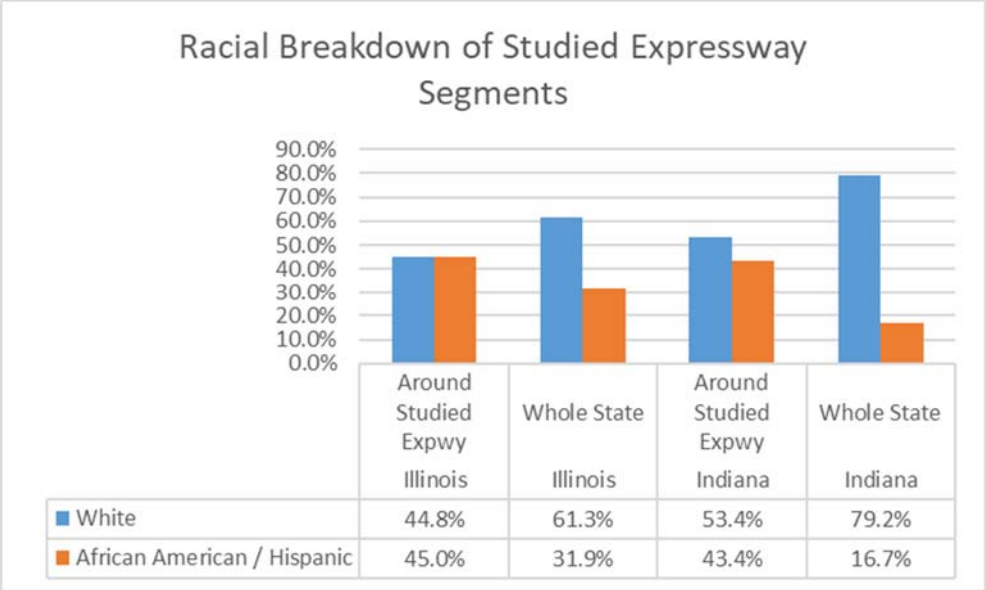
The study finds that for the 1.87 million people living next to the 500 miles of major expressways in the Chicago/NW Indiana region we expect a reduction of 9 lifetime cancer cases with a total lifetime savings in monetary damages of $81 million. However, we only assessed cancer cases for selected toxic air compounds, exposed to a fraction (0.6 percent) of the US population. The total urban share of the US population is currently cited at 80.7 percent which would mean that 264 million of the current 327 million people in this country live in urban clusters. If we view our results as a first, approximate calibration of how urban areas are affected by air toxins then the extrapolation of this data would result in an upper bound cancer reduction for the studied toxic air compounds of 1,256 cases and avoided lifetime monetary damages of $11.4 billion.

Summary of Health Impact and First Order Extrapolation

Cancer Case Reductions Chicago Major Expressway Area	9
Affected Population Chicago Major Expressway Area	1,873,456
Value of Statistical Life (VSL)	$9,100,000
Monetary Damages Avoided Chicago Major Expressways Area	$81,076,048
Urban Share of US Population	81%
US Population	327,200,000
US Urban Population	264,050,400
Upper Bound Extrapolation of Results	
Cancer Cases	1,256
Monetary Damages Avoided	$11,427,096,739

Moreover, for the Chicago/NW Indiana region a significant upward adjustment can also be justified. With 9.5 million people living in the Chicago Metro area and many along other major roadways (in addition to the 1.87 million studied) the assessed cancer cases will also likely be a multiple of our selected modeling subset.

Importantly, the present study also documents that the share of minority groups living within the vicinity of polluting expressways is much higher than their respective share in each studied state (Indiana and Illinois). This means that the derived cancer reductions from ethanol-blended high-octane gasoline will likely over-proportionally benefit minority groups.



Racial Breakout Between State Totals and Studied Area

Introduction

The University of Illinois at Chicago Energy Resources Center has conducted a study to assess toxic air compound related cancer reductions from the use of high octane ethanol blended gasoline. The geographic focus of the study is along 500 miles of expressway segments in the Chicago and Northwest Indiana road corridor. Using data from this limited geographic area the study attempts to estimate an upper bound of health impacts on a national level. Given the thin datasets on high octane fuel vehicle emissions studies and modeling limitations this number serves as an approximation of the air toxins health impacts from the use of high-octane E25 fuels with clearly understood uncertainties.

Methodologically, the present study follows an EPA developed case study of the benefits of the Clean Air Act on benzene emissions in the Houston area but with newly developed, updated models.[16] The purpose of the EPA case study was to "demonstrate a methodology that could be used to generate human health benefits from the US Clean Air Act in an urban setting."

EPA found that over a 30-year study period "the change in benzene-related population risk due to the 1990 CAAA programs would be equivalent to a total of four cases of leukemia in the Houston area" (see Appendix A). EPA states:

> "Although the actual benefit results appear modest, we note that leukemia is a rare disease with a low baseline rate among the population - for people under 50, the baseline risk in the study area was generally less than 5 in 100,000. Therefore, even significant percentage reductions in the baseline leukemia mortality rate may translate to relatively small numbers of avoided cases. We also note that the cases avoided are associated with only three U.S. counties containing just over one percent of the total U.S. population. We would expect significantly higher numbers of leukemia cases avoided when looking nationally at benzene reductions."

This EPA case study was chosen as a model because it quantifies the health benefits of a selected compound. In a similar way, ethanol adjusts the emissions profile of several, particularly carcinogenic toxic air compounds and following the EPA benzene modeling exercise therefore allows us to identify those benefits in a proven framework.

[16] https://www.epa.gov/sites/production/files/2015-07/documents/812caaa_benzene_houston_final_report_july_2009.pdf
Also detailed in: The Benefits and Costs of the Clean Air Act from 1990 to 2020; Final Report – Rev. A ; U.S. Environmental Protection Agency Office of Air and Radiation; April 2011)

Key Air Emissions Compounds Affected by Ethanol Blends

Gasoline contains a large amount of aromatic hydrocarbons that are added to gasoline because they have relatively high octane values and therefore serve as anti-knock agents in vehicle engines. Some aromatics are toxic compounds. Ethanol also has a high octane value and contains no aromatic compounds. It therefore substitutes and dilutes aromatics in gasoline. Moreover, ethanol also alters the distillation curve resulting in an adjustment of the distillation properties of the fuel with, for example a higher volume fraction of the fuel distilled at 200 degrees Fahrenheit. This effect further reduces the formation of toxic emissions in a vehicle.

Some of the most toxic air compounds from vehicle emissions include benzene, 1,3 butadiene, formaldehyde, acetaldehyde and a group of compounds called polycyclic aromatic hydrocarbons (PAHs). Some of these compounds are either in the vapor phase (benzene, 1,3 butadiene, formaldehyde, acetaldehyde) or the particulate phase. In general, PAHs with two or three benzene rings existed in the vapor phase, whereas PAHs with more than five rings were observed mainly in the particulate phase.[17] Benzo[a]pyrene, one of the most carcinogenic PAHs from vehicle exhaust has 5 fused benzene rings and is predominantly in the particulate phase. PAHs in the particulate phase are mostly bound to PM 2.5 and the ultrafine fraction of the airborne particulates that are reportedly known for their higher health risk.

The health impact of inhaling the considered toxic air compounds is summarized below:[18]

A) Emissions compounds in the volatile organic group:

Acetaldehyde. Acetaldehyde has been classified as *possibly carcinogenic to humans* (Group 2B) by the International Agency for Research on Cancer. The US EPA classifies acetaldehyde as a probable human carcinogen based on nasal and laryngeal tumors observed in rodents after inhalation exposure.

[17] Polycyclic Aromatic Hydrocarbons Bound to PM 2.5 in Urban Coimbatore, India with Emphasis on Source Apportionment; R. Mohanraj; ScientificWorldJournal; https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3350969/

[18] Multiple citations for this section:

- US EPA Integrated Risk Information System Chemical Assessment Summary: Acetaldehyde. https://cfpub.epa.gov/ncea/iris/iris_documents/documents/subst/0290_summary.pdf
- R Baan, Y Grosse, K Straif, B Secretan, F El Ghissassi, V Bouvard et al. (2009) A review of human carcinogens – Part F: Chemical agents and related occupations. Lancet 10(120: 1143-1144
- IARC Monographs Volume 100F. Chemical Agents and Related Occupations (2012) Lyon: France
- Toxicological Review of Benzo[a]pyrene: Executive Summary. EPA/635/6-17/003Fc (2017). https://cfpub.epa.gov/ncea/iris/iris_documents/documents/subst/0136_summary.pdf
- IARC Monographs Volume 100F. Chemical Agents and Related Occupations (2012) Lyon: France
- H Checkoway, P Boffetta, DJ Mundt, KA Mundt (2012) Critical review and synthesis of the epidemiologic evidence on formaldehyde exposure and risk of leukemia and other lymphohematopoietic malignancies. Cancer Causes Control 23(11): 1747-1766.
- L Zhang, C Steinmaus, DA Eastmond, XK Xin, MT Smith (2009) Formaldehyde exposure and leukemia: a new meta-analysis and potential mechanisms. Mut Res 681(2-3): 150-168.

Benzene. Benzene has been classified as *carcinogenic to humans* (Group 1) by the International Agency for Research on Cancer. Benzene causes acute myeloid leukemia (acute non-lymphocytic leukemia), and has been positively associated with acute lymphocytic leukemia, chronic lymphocytic leukemia, multiple myeloma and non-Hodgkin lymphoma.

Butadiene. 1,3-butadiene has been classified as *carcinogenic to humans* (Group 1) by the International Agency for Research on Cancer. 1,3-butadiene has been associated with cancer of the haematolymphatic organs, such as leukemia.

Formaldehyde. Formaldehyde has been classified as *carcinogenic to humans* (Group 1) by the International Agency for Research on Cancer. There is scientific consensus that formaldehyde contributes to the development of cancer in the nasal tissues, though the association with lymphohematopoietic cancers is more controversial.

B) Emissions compounds mostly in the particulate phase

Polycyclic Aromatic Hydrocarbons (PAHs)

Polycyclic aromatic hydrocarbons (PAHs): This category is defined as hydrocarbons containing fused aromatic rings. These compounds can be measured in the gaseous phase, particulate phase, or both, depending on properties of the compound, particle characteristics and conditions in the exhaust stream or the atmosphere. Benzopyrene is one of the most carcinogenic PAHs. Appendix B indicates that Fuoranthene, Benzoapyrene, Phenanthrene, Benzofluranthene, and Chrysene/triphenylene are particularly dominant PAHs in vehicle exhaust.

Benzo[a]pyrene (BaP). BaP has been classified as *carcinogenic to humans* (Group 1) by the International Agency for Research on Cancer. The basis for this classification is a clear mechanism of genotoxicity that impacts lung tumors, though epidemiologic studies have observed increased lung and skin cancer risks. Animal studies have observed cancers at many locations after exposure to BaP in mixtures through multiple routes.

BaP is one of many polycyclic aromatic hydrocarbons (PAHs) emitted in vehicle exhaust, many of which are thought to be carcinogenic. For this analysis, BaP is used as an indicator of carcinogenic risk from PAHs because it is the most potent of the PAHs, and has been found to dominate the cancer risk posed by PAHs emitted by gasoline vehicles.

Many additional pollutants in vehicle exhaust adversely impact health, or are formed from vehicle emissions, but are not specifically quantified in this study.

Emissions Estimation

We employed the following modeling approach: In a first step the EPA MOVES2014b model was used to model emissions for gasoline without ethanol (E0) for the Chicago metro area and Northwest Indiana (Chicago-NWI) Expressway segments. From these model runs we extracted the resulting toxic air compound emissions rates in mass of emissions per distance driven (milligram/mile). In a next step the mass emissions were converted into concentrations using the CAL3QHC model for the Chicago-NWI expressway segments. CAL3QHC is an air quality model based on the CALINE3 model which can be used to predict the concentrations of select criteria pollutants and other user-defined inert pollutants near highways.[19] Given source strength, meteorology and site geometry, the model can predict pollutant concentrations for receptors located within 500 meters of the roadway. Source strength is also a function of traffic totals.

The geographic area for the CAL3QHC parameterization is shown in Figure 1. The expressway segments cover a total of 500 miles bound by the Chicago suburb of Elgin in the North, Aurora to the West, South Bend, Indiana in the East, and Crown Point, Indiana in the South. The map below highlights the studied expressway segments and shows the approximate receptor distances from the road centerlines. For this study we divided the expressway system into 44 individual segments (see Appendix C for segment and traffic details). A sample CAL3QHC map for two of the expressway segments can be found in Appendix D. Using ARC-GIS we identified that 1.87 million people live within 0.6 miles on each side of these roadways. We also broke down the population by racial groups (see Table 1).

Figure 1: Population Across the Geographic Study Area

[19]EPA Air Quality Dispersion Modeling – Preferred and Recommended Models https://www.epa.gov/scram/air-quality-dispersion-modeling-preferred-and-recommended-models

Table 1: Population Characteristics Around Expressway Segments

	Illinois	Indiana	total
Expressway Miles Studied	338.1	162.27	500.37
Population Around Studied Expressways	1,724,877	148,579	1,873,456
White %	44.80%	53.40%	
Hispanic %	16.80%	17.80%	
African American %	28.20%	25.60%	
Statewide Population	12,741,080	6,691,878	
White %	61%	79%	
Hispanic %	17%	7%	
African American %	15%	10%	

The table below shows the derived pollutant concentrations from CAL3QHC averaged for all expressway segments. The spreadsheet model that is posted as supporting information to this report allows to disaggregate these concentrations by expressway segment.

Table 2: Modeled Pollutant Concentrations from E0 Along Chicago NW Indiana Expressways

	ug/m3
	E0
Benzene	0.256844
Formaldehyde	0.055661
1,3-Butadiene	0.031759
Acetaldehyde	0.023572
Acrolein	0.003929
Anthracene gas	0.000163
Anthracene particle	0.000003
Benz(a)anthracene gas	0.000026
Benz(a)anthracene particle	0.000026
Benzo(a)pyrene gas	0.000001
Benzo(a)pyrene particle	0.000064
Benzo(b)fluoranthene gas	0.000020
Benzo(b)fluoranthene particle	0.000031
Benzo(g,h,i)perylene particle	0.000174
Benzo(k)fluoranthene gas	0.000020
Benzo(k)fluoranthene particle	0.000031
Chrysene gas	0.000029
Chrysene particle	0.000022
Fluoranthene gas	0.000273
Fluoranthene particle	0.000010
Indeno(1,2,3,c,d)pyrene gas	0.000000
Indeno(1,2,3,c,d)pyrene particle	0.000065
Phenanthrene gas	0.001043
Phenanthrene particle	0.000010
Pyrene gas	0.000312
Pyrene particle	0.000011

Emissions Adjustments with E25

MOVES2014b is not set up for higher ethanol blends such as E25 so we had to rely on recent vehicle studies. Therefore, a thorough review of the global literature was conducted of emissions adjustments with E10 relative to E0 and studies using E20-E25 fuel blends relative to E0 (or E20/E25 blends relative to E10). We then averaged the emissions reductions for all vehicle studies. Table 3 below shows the result of the literature review.

Table 3: Emissions Adjustments from Ethanol Blends

Study Name	Pollutant	Karavalakis et al., 2012	Bertoa et al., 2015	SAE, 1992	NREL, 2009	Storey et al., 2010	ORNL 2012	Schifter et al., 2011	Graham et al., 2008	Bielaczyc et al., 2013	Knapp et al. 2011	Yao et al., 2011	Czerwinski et l., 2016	Martini et al., 2009	Munoze et al 2016 ES&T	MOVES 2014 Chicago	AVERAGE
Vehicles		1984-2007 Gasoline vehicles (Total 6), One additional 2007 Flex Fuel Vehicle	One Euro 5a flex-fuel light duty vehicle (FFV) equipped with a three way catalyst (TWC) and a turbo	Ford Valencia SI engine	1999-2007 Gasoline vehicles (Total 16)	2007 Pontiac Solstice	19 Tier 2 and 8 Tier 1/NLEV	4 vehicles older than 1992, 17 vehicles between 1993 - 1997 and 9 vehicles	Two 2002 LEV 1 LDT and One 2004 ULEV 1	One Euro V vehicle	1977 - 1994 Gasoline vehicles (Total 11 No.s)	2000 and 2005 passenger cars	new (Euro 5) flex fuel vehicle Volvo V60 (GDI)	Euro IV Ford Focus flexible fuel car	Flex fuel Euro-5 GDI vehicle		
Test cycle		FTP-75	WLTC		LA 92	FTP-75, US06	FTP-75	FTP-75	FTP-75, US06	NEDC	UDDS	FTP-75	WLTC	NEDC	WLTC		
Location		California	Italy	United States	United States	United States	United States	Mexico	Canada	Poland	Alaska	Taiwan	Switzerland	Italy	Switzerland		
E10 Relative to E0	PM					-6.0%				-19.7%				-26.0%			-17.2%
	Benzene	-29.0%	-56.0%	-11.5%				-10.0%	15.0%	-20.8%	-20.1%	-18.0%		17.9%			-14.7%
	1,3-butadiene	-30.0%		-5.8%				6.8%	16.0%		-14.3%			-63.6%			-15.2%
	Formaldehyde	-44.0%	-50.0%	19.3%	-85.0%	-29.0%	-96.0%	0.0%	5.0%	75.0%	-40.0%	11.2%	-17.2%	-5.0%			-19.7%
	Acetaldehyde	16.0%	133.0%	159.0%	9.0%	95.0%	17.0%	19.2%	108.0%	5.9%	#####	20.6%		149.0%			99.6%
	Fluoranthene														-60.9%	-8.6%	-34.7%
	Benzoapyrene*														-27.6%	-8.6%	-18.1%
	Phenanthrene														-71.1%	-8.6%	-39.9%
	Benzofluranthene														-81.0%	-8.6%	-44.8%
	Chrysene														-79.8%	-8.6%	-44.2%
E20/25 Relative to E0	PM					-29.0%											-29.0%
	Benzene	-36.0%							26.3%			-28.9%					-12.9%
	1,3-butadiene	-56.0%							0.0%								-28.0%
	Formaldehyde	-36.0%			-85.0%	-31.0%	-81.0%		61.5%			16.6%					-25.8%
	Acetaldehyde	101.0%			131.0%	250.0%	161.0%		200.0%			37.5%					146.8%
	Fluoranthene																-56.7%
	Benzoapyrene*																-52.6%
	Phenanthrene																-82.6%
	Benzofluranthene																-87.9%
	Chrysene																-89.4%

Only a couple of vehicle emissions studies have explored the impact of ethanol on PAH emissions. We combined PAH reductions documented in a study by the Swiss Federal Laboratories for Materials Science and Technology for E10 relative to E0 with very recent vehicle testing conducted by Oak Ridge National Laboratory for E25 relative to E10.[20]

Oak Ridge National Laboratory performed fuel economy and emissions tests for a GMC Terrain vehicle. The GMC Terrain vehicle emissions tests are based on 92-93 RON Tier 3 E10 and 99 RON E25 fuels. However, quantification of PAH emissions was not part of the original scope of

[20] Bioethanol Blending Reduces Nanoparticle, PAH, and Alkyl- and Nitro-PAH Emissions and the Genotoxic Potential of Exhaust from a Gasoline Direct Injection Flex-Fuel Vehicle; Maria Muñoz et al. ; Swiss Federal Laboratories for Materials Science and Technology; Environ. Sci. Technol. 2016, 50, 11853−11861

that study. As part of the present study we obtained the filters and conducted a Gas Chromatography/Mass Spectrometry analysis for those filters at The Hormel Institute-University of Minnesota-Mayo Clinic (THI data).[21] With that we documented additional emissions reductions for the most prevalent and carcinogenic PAHs from vehicle exhaust from adopting high octane E25 over E10. Table 4 shows that an increase in ethanol blends from E10 to E25 would further reduce selected PAHs by over 30 percent. Combining these results with the emissions reductions show from the Swiss study resulted in the overall expected reductions for E25 over E0 shown for PAHs in Table 3 (highlighted cells in blue).

Table 4: PAH Reduction from THI Analysis

PAH Compound	THI Data E25 over E10 Percent Reduction	Combined Data E25 over E0
Fluoranthene	-33.7%	-56.7%
Benzoapyrene*	-34.6%	-52.6%
Phenanthrene	-39.6%	-82.6%
Benzofluranthene	-36.3%	-87.9%
Chrysene/triphenylene	-47.5%	-89.4%

[21] https://www.hi.umn.edu/

Cancer Outcomes and Impacts

We estimated the impact of ethanol fuels on cancer outcomes as follows: first we calculated the cancer risk for E0 by multiplying the affected population living around our studied expressway segments by inhalation unit risk factors for each pollutant. Then we quantified the percent reductions from E25 adoption (last column in Table 2).

The inhalation unit risk (IUR) factor is a standard metric for estimating excess lifetime cancer risk associated inhalation exposure, and assumes a lifetime of continuous exposure. The IUR factor has units of risk per 1 ug/m^3 inhalation exposure. The IUR factors used in this study are shown in the table below, and were derived by the California Office of Environmental Health Hazard Assessment (OEHHA). The OEHHA values were selected because they tend to be more health-conservative than values derived by the US EPA.[22]

For polycyclic aromatic hydrocarbons additional clarification is required. Vehicle exhaust contains a host of PAHs which are more or less carcinogenic. The carcinogenicity of BaP is well studied and toxic equivalency factors to characterize other PAHs have been developed. However, the cancer risk is dominated by BaP for newer and older gasoline cars (see Appendix B). Therefore, we followed the approach described in Bostrom et al: [23] "in the past, EPA has assessed risks posed by mixtures of PAHs by assuming that all carcinogenic PAHs are as potent as benzo[a]pyrene (B[a]P), one of the most potent PAHs." We also acknowledge the statement in Bostrom et al that this approach is likely overestimating the risk.

Table 5. Inhalation Unit Risk (IUR) factors for selected carcinogens in vehicle exhaust

Pollutant	IUR Factor (risk per ug/m^3)	Relative Potency
Acetaldehyde	2.7×10^{-6}	0.002
Benzene	2.9×10^{-5}	0.026
Benzo[a]pyrene	1.1×10^{-3}	1.00
1,3-Butadiene	1.7×10^{-4}	0.155
Formaldehyde	6.0×10^{-6}	0.005

The change in the number of cases of cancer estimated to result from the introduction of ethanol fuels relative to the continued use of gasoline is shown in the table below. The emissions for the "possibly known carcinogen in humans" acetaldehyde is estimated to slightly increase with the use of ethanol fuels but the increase is very small relative to the decreases seen for other compounds.

[22] OEHHA 2009. Air Toxics Hot Spots Program Technical Support Document for Cancer Potencies. Appendix B. Chemical-specific summaries of the information used to derive unit risk and cancer potency values. Updated 2011. https://oehha.ca.gov/media/downloads/risk-assessment/report/appbraac.pdf

[23] Bostrom et al. (2002) Environmental Health Perspectives 110(S3): 451-488.

Table 6: Cancer Cases for E0 and E25 for Selected Pollutants

	Cancer Cases	Cancer Cases
Pollutant	**E0**	**E25**
Benzene	14.60	12.7
Formaldehyde	0.65	0.5
1,3-Butadiene	10.58	7.6
Acetaldehyde	0.12	(0.1)
Acrolein		-
Anthracene gas	0.35	0.09
Anthracene particle	0.01	0.00
Benz(a)anthracene gas	0.06	0.01
Benz(a)anthracene particle	0.06	0.01
Benzo(a)pyrene gas	0.00	0.00
Benzo(a)pyrene particle	0.14	0.04
Benzo(b)fluoranthene gas	0.04	0.01
Benzo(b)fluoranthene particle	0.07	0.02
Benzo(g,h,i)perylene particle	0.37	0.10
Benzo(k)fluoranthene gas	0.04	0.01
Benzo(k)fluoranthene particle	0.07	0.02
Chrysene gas	0.06	0.02
Chrysene particle	0.05	0.01
Fluoranthene gas	0.59	0.15
Fluoranthene particle	0.02	0.01
Indeno(1,2,3,c,d)pyrene gas	0.00	-
Indeno(1,2,3,c,d)pyrene particle	0.14	0.04
Phenanthrene gas	2.25	0.59
Phenanthrene particle	0.02	0.01
Pyrene gas	0.67	0.18
Pyrene particle	0.02	0.01
	31	**22**
Difference	**9**	

As can be seen the adoption of E25 reduces cancers from the selected pollutants by 9 cases. Multiplied 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 savings of $81 million.[24;25] Similarly to the EPA Houston Benzene Case Study the results appear, at first glance, modest.

However, we only assessed cancer cases for selected toxic air compounds for the 1.87 million people living next to the major expressways in the Chicago/NW Indiana region, which make up 0.6 percent of the US population. The total urban share of the US population is currently cited at 80.7 percent which would mean that 264 million of the current 327 million people in this country live in urban clusters.[26;27] The visualization of traffic across urban clusters provided in Appendix E provides further support that the studied area is only a very small subset of the likely total US impact. If we view our results as a first approximate calibration, then the extrapolation of this data would result in an upper bound cancer reduction for the studied toxic air compounds of 1,256 cases and avoided lifetime monetary damages of $11.4 billion.

Table 7: Summary of Health Impact and First Order Extrapolation

Cancer Case Reductions Chicago Major Expressway Area	9
Affected Population Chicago Major Expressway Area	1,873,456
Value of Statistical Life (VSL)	$9,100,000
Monetary Damages Avoided Chicago Major Expressways Area	$81,076,048
Urban Share of US Population	81%
US Population	327,200,000
US Urban Population	264,050,400
Upper Bound Extrapolation of Results	
Cancer Cases	1,256
Monetary Damages Avoided	$ 11,427,096,739

Similarly, for the Chicago region an upward adjustment can be justified. With 9.5 million people living in the Chicago Metro area and many along other major roadways (in addition to the 1.87 million studied) the assessed cancer cases will also likely be a multiple of our selected modeling subset.[28]

For additional context, other regulatory actions have been taken to prevent numbers of cancers that seem modest relative to the total burden of disease. For example, in the reduction of the Permissible Exposure Limit for 1,3-butadiene in the United States to 1 ppm was estimated by the Occupational Safety and Health Administration to avoid 59 cancers among approximately 9000 exposed workers over a working lifetime of 45 years, or 1.3 cancers per year.[29] Costs to

[24] Technical Support Document. Estimating the Benefits per Ton of Reducing PM2.5 Precursors from 17 Sector. US EPA Office of Air and Radiation, 2013.
[25]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
[26] https://en.wikipedia.org/wiki/Urbanization_in_the_United_States
[27] https://www.census.gov/history/www/programs/geography/urban_and_rural_areas.html
[28] https://en.wikipedia.org/wiki/Chicago_metropolitan_area
[29] Occupational Exposure to 1,3-butadiene. Final Rule. Federal Register 61: 56746-56856. (1996).

employers to comply with the new 1,3-butadiene standard was estimated to be $2.9 million in 1996 dollars annually, or approximately $2.3 million per cancer avoided per year. Similarly, the reduction in the Permissible Exposure Limit for benzene from 10 ppm to 1 ppm was estimated by the Occupational Safety and Health Administration to avoid 326 deaths from leukemia and other lymphohematopoietic cancers over 45 years, or 7.2 cancers per year; a reduction of similar magnitude to the presented ethanol blended gasoline efforts.[30] Costs to employers to comply with the new benzene standard was estimated to be $24 million in 1986 dollars annually, or $3.3 million per cancer avoided per year.

Potential Impact on Racial Inequities

We also assessed the racial breakout within the studied road segment. The map below shows the amount of minorities (for simplification purposes defined as African Americans plus Hispanics) in census tracts within 0.6 miles on each side of these roadways.

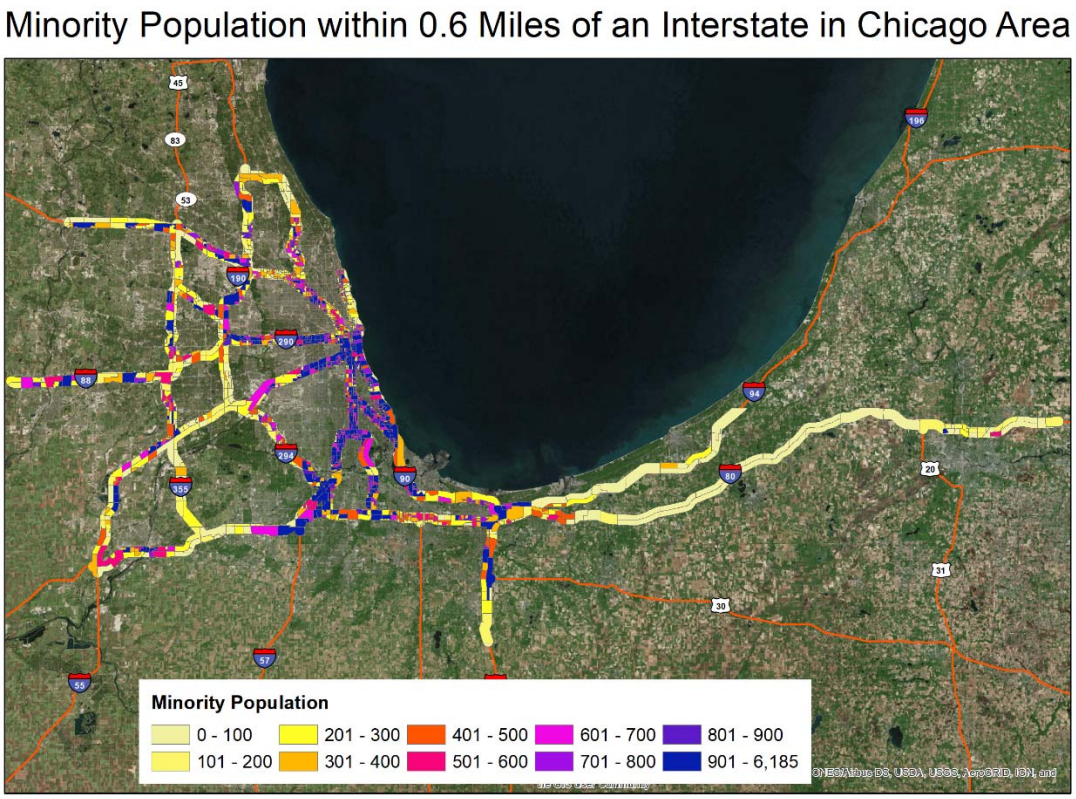
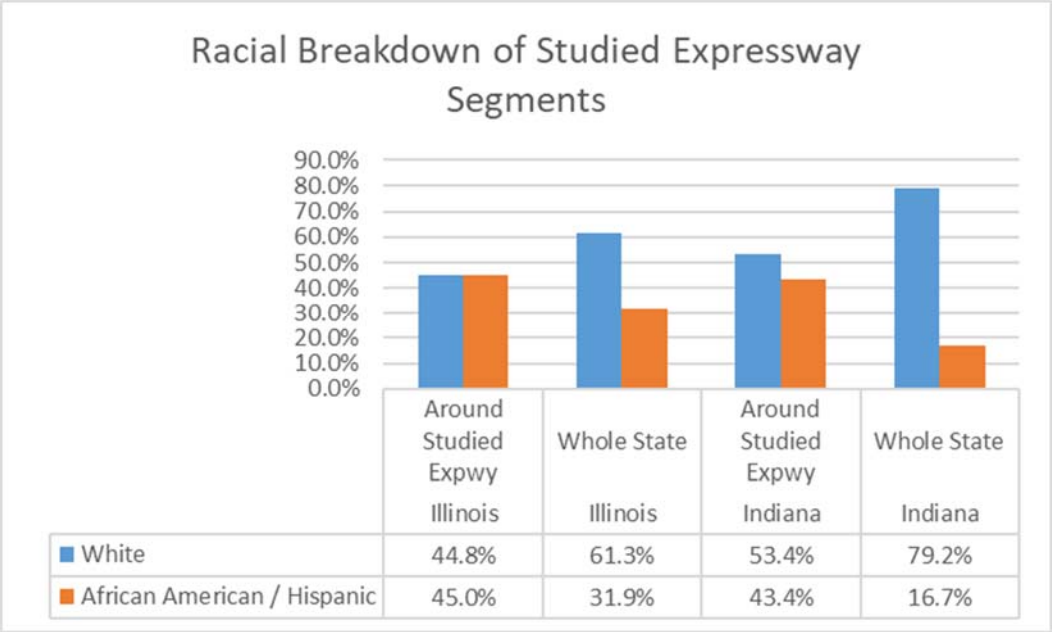


Figure 2: Racial Breakout Across the Study Area

The table and graph summarizes the racial breakouts. As can be seen statewide Illinois is home to 61.3% whites and 31.9% African-American/Hispanics but around the studied expressway segments in Illinois a much higher percentage of 45% is African Americans/Hispanics. Likewise, statewide Indiana is home to 79.2% whites and 16.7% African America/Hispanics but around the studied expressway segments in Indiana a much higher percentage of 43.4% is African

[30] Occupational Exposure to Benzene: Final Rule. Federal Register 52(1786): 34460-34578 (1987)

Americans/Hispanics. This means that the derived cancer reductions from high-octane ethanol blended gasoline will likely over-proportionally benefit minority groups.



	Around Studied Expwy Illinois	Whole State Illinois	Around Studied Expwy Indiana	Whole State Indiana
White	44.8%	61.3%	53.4%	79.2%
African American / Hispanic	45.0%	31.9%	43.4%	16.7%

Figure 3: Racial Breakout Between State Totals and Studied Area

Appendix A: EPA Benzene Case Study

THE UNIVERSITY OF ILLINOIS AT CHICAGO

Benzene EPA Carcinogen Case Study

- Houston: 4 annual cases of Leukemia across 3 million people

TABLE 5-9. TOTAL ANNUAL BENEFITS FOR EACH STUDY YEAR FROM CAAA-RELATED CHANGES IN BENZENE EXPOSURE IN THE HOUSTON AREA

	ANNUAL AVOIDED CASES OF LEUKEMIA			TOTAL MONETARY BENEFITS, 1990 TO 2010 (1990 HPV, MILLIONS OF 2006$, 5% DISCOUNT RATE)		
	AVOIDED FATAL CASES	AVOIDED NON-FATAL CASES	TOTAL AVOIDED CASES	BENEFITS FROM FATAL CASES OF LEUKEMIA	BENEFITS FROM NON-FATAL CASES OF LEUKEMIA	TOTAL BENEFITS
Results by Study Year						
2000	0.03	0.02	0.05	$0.12	$0.01 - 0.06	$0.13 - 0.18
2010	0.09	0.07	0.2	$0.27	$0.01 - 0.13	$0.28 - 0.40
2020	0.2	0.1	0.3	$0.31	$0.01 - 0.15	$0.32 - 0.46
Cumulative Results						
Cumulative Cases Occurring Within the Study Period	2	2	4	$6.7	$0.32 - 3.3	$7.0 - 10
Additional Cumulative Cases Occurring after 2020*	1	1	2	$1.8	$0.08 - 0.8	$1.9 - 2.6
Total Cumulative Cases	3	3	6	$8.5	$0.40 - 4.1	$8.9 - 13

* Note: These avoided cases are due to changes in benzene exposure that took place within the study period. However, the cases occurred after 2020 due to lagging effects of these changes on leukemia risks, as described in the text.

UIC ENGINEERING

Appendix B: PAHs in Vehicle Exhaust

THE UNIVERSITY OF ILLINOIS AT CHICAGO

Cancer Risk from PAHs for Emissions from Gasoline Vehicles

- Cancer risk is dominated by B[a]P

Table 15. The relative contribution of individual PAHs[a] to B[*a*]P equivalents calculated for emissions from gasoline and diesel engines.[b]

		Light-duty vehicles			Heavy-duty trucks	
PAH	TEF[c]	Gasoline without catalytic converter	Gasoline + three-way catalytic converter	Diesel light (MK1) + oxidizing catalytic converter	Diesel (MK3) without catalytic converter	Diesel (MK1) without catalytic converter
		% of total B[a]P equivalents				
Anthracene	0.0005	0.2	0.4	0.1	0.3	0.1
Benz[a]anthracene	0.005	0.2	0.3	0.1	0.4	[d,e]
B[a]P	1	77	43	5.3	4.2	7.1[e]
Benzo[b and j]fluoranthene	0.075	4.4	11	1.6	0.8	0.5[e]
Benzo[ghi]perylene	0.02	1.4	1.4	0.2	[d,e]	0.1[e]
Chrysene/triphenylene	0.03[f]	1.4	4.3	1.6	0.6	0.4
Fluoranthene	0.05	12	36	88	86	85
Indeno[1,2,3-cd]pyrene	0.1	2.3	1.4	0.5	0.2[e]	0.7[e]
Phenanthrene	0.0005	0.5	2.0	1.0	2.8	1.4
Pyrene	0.001	0.3	0.4	1.3	4.4	4.9
Total (µg/km)		8.6	0.7	1.9	4.8	1.4

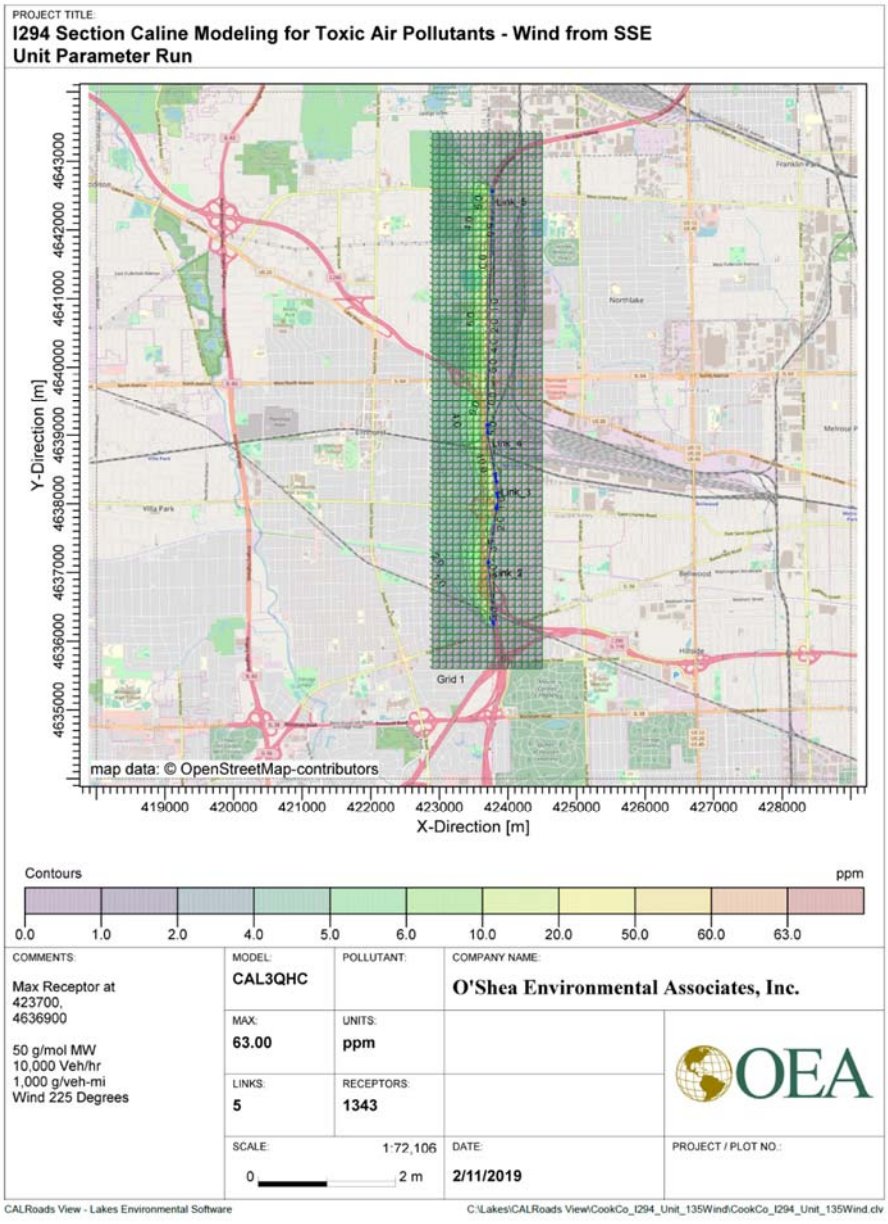
[a]Note that the sum is calculated for the given individual PAH only, although there are other PAHs present in the emissions that might also contribute to the carcinogenic risk of the emissions. [b]For concentrations of individual PAHs, see Table 5. [c]Data from Larsen and Larsen 1998. [d]Concentration below the detection limit. The detection limit is used for calculations. [e]Below 0.1%. [f]TEF for chrysene.

Source: Cancer Risk Assessment, Indicators, and Guidelines for Polycyclic Aromatic Hydrocarbons in the Ambient Air
Carl-Elis Boström et al; Environmental Health Perspectives • VOLUME 110 | SUPPLEMENT 3 | JUNE 2002

Appendix C: Traffic Totals by Expressway Segment

Highway Name	Map Segment	Average Daily Traffic Totals	Average Hourly Traffic Totals
Stevenson Expressway	I-355 to I-294	155,850	6,494
Stevenson Expressway	I-294 to Dan Ryan I-90 & I94	167,150	6,965
Stevenson Expressway	I-80 to I-355	100,542	4,189
I-57 Expressway	I-80 to Dan Ryan	131,350	5,473
I-80 Expressway	I-355 to I-57	98,800	4,117
I-80 Expressway	I-57 to I294	88,700	3,696
I-80 Expressway	I-55 to I-355	70,200	2,925
Kingery Expressway	I94 to Indiana State Line	149,600	6,233
Dan Ryan Expressway	I-90 Skyway to 95th Street	245,650	10,235
Dan Ryan Expressway	63rd Street to I-55	296,000	12,333
Kennedy Expressway	I-190 from Bessie Coleman to I-90	77,200	3,217
Kennedy Expressway	I-90 from Cumberland to Lawrence	171,250	7,135
Kennedy Expressway	I90/94 from Edens to Randolph	247,800	10,325
Bishop Ford Freeway	Route 394 to Dan Ryan	157,350	6,556
Edens Expressway	Clavey Rd to Kennedy Exp.	139,000	5,792
Eisenhower Expressway	I294 to I90/94	169,650	7,069
I-290 Extension	I-90 to I-290	140,900	5,871
Elgin O'Hare	US 20 to I-290 Thorndale	50,600	2,108
Illinois Route 53	I-90 Jane Addams Memorial Toll. to Thorndale Ave.	140,900	5,871
Veterans Memorial Tollway I-355	I-80 to I-55	73,890	3,079
Veterans Memorial Tollway I-355	I-55 to I-88	129,735	5,406
Veterans Memorial Tollway I-355	I-88 to Army Trail Road	142,010	5,917
Tri-State Tollway I-294	Bishop Ford to 95th Street	150,095	6,254
Tri-State Tollway I-294	95th Street to I-55	155,455	6,477
Tri-State Tollway I-294	I-55 to I-88	168,680	7,028
Tri-State Tollway I-294	I-88 to I-290	167,605	6,984
Tri-State Tollway I-294	I-290 to I-94	141,590	5,900
Reagan Memorial Tollway	I-355 to I-294	144,110	6,005
Reagan Memorial Tollway	Dekalb to I-355	49,280	2,053
Jane Addams Memorial Tollway	Tri State to Rt 53	259,740	10,823
Jane Addams Memorial Tollway	Rt. 53 to Elgin (Randall Rd.)	103,960	4,332
Lake Shore Drive	Hollywood to Balbo	133,650	5,569
Lake Shore Drive	Roosevelt Rd. to Jeffery Blvd.	85,950	3,581
Chicago Skyway	Dan Ryan to Indiana State Line	36,147	1,506
Indiana I-90	Indiana State Line to I-65	36,147	1,506
I-80 Expressway	Indiana State Line to I-65	175,818	7,326
I-80 Expressway	I-65 to Rt. 421	107,523	4,480
I-80 Expressway	Rt. 421 to Rt. 933	110,255	4,594
I-80 Expressway	Rt. 933 to US 35	74,494	3,104
I-94	I-65 to SR 49	70,157	2,923
I-94	SR 49 to US 35	59,008	2,459
I-94	US 35 to Michigan State Line	42,727	1,780
I-65	I-80 to US 30	99,427	4,143
I-65	US 30 South	55,908	2,330

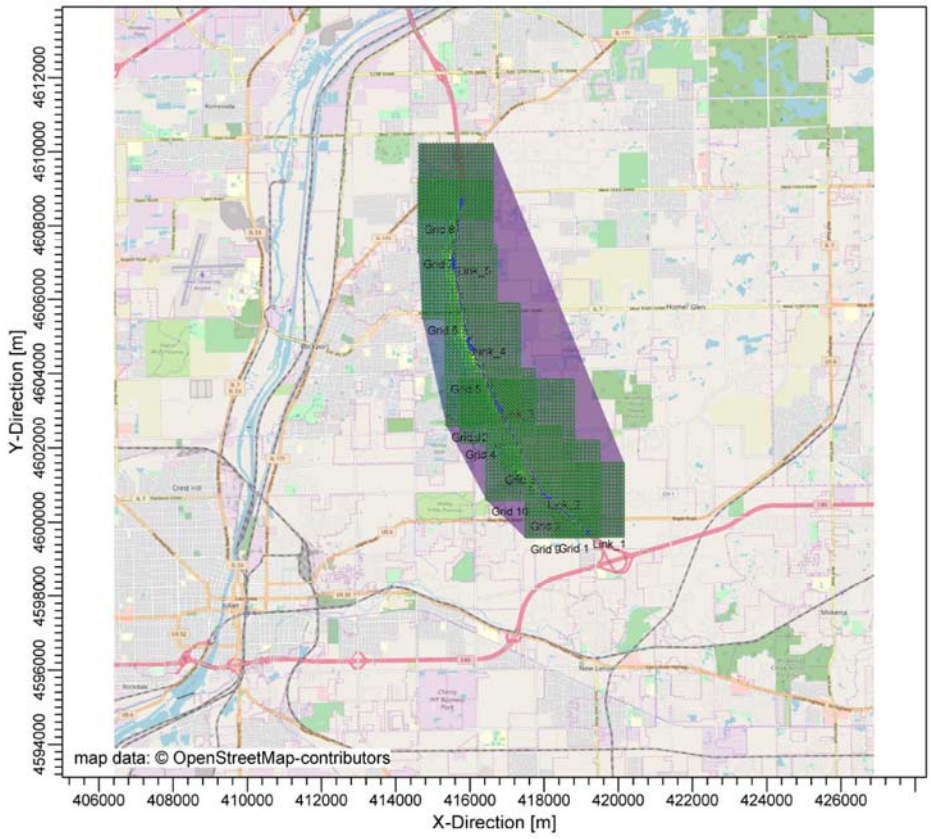
Appendix D: Selected CALINE Runs



UIC ENGINEERING

PROJECT TITLE:

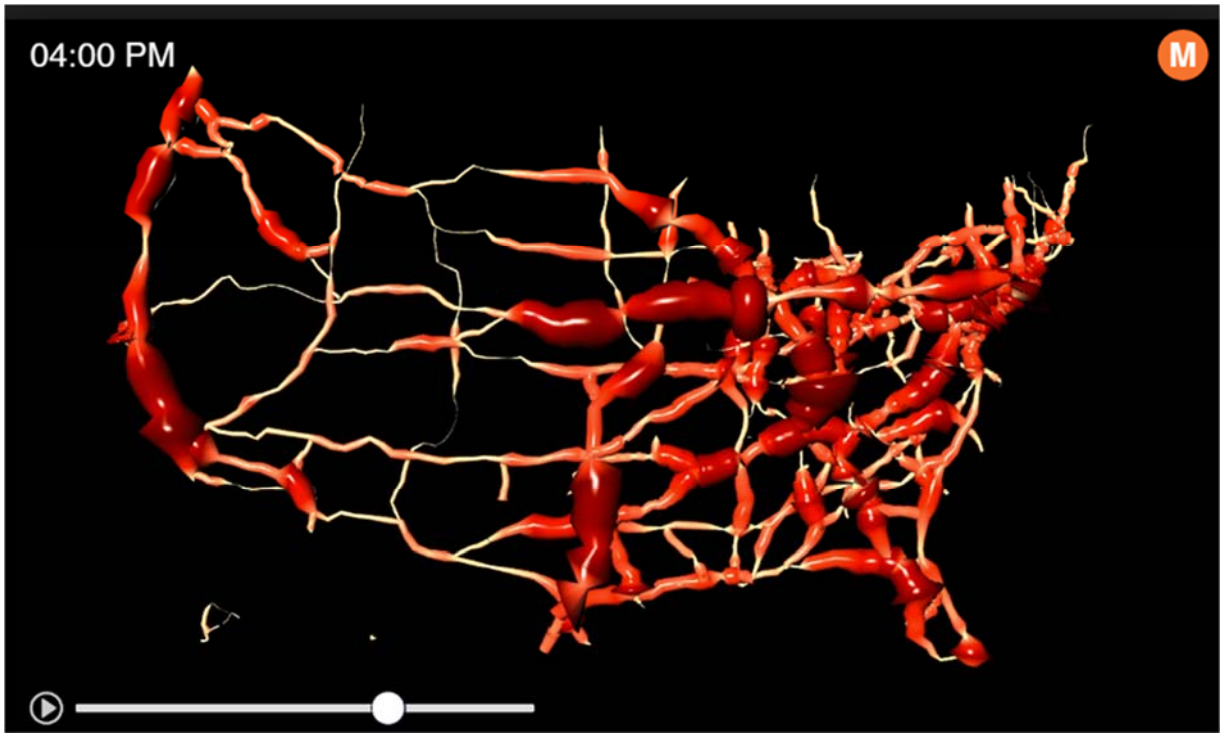
I355 Section Caline Modeling for Toxic Air Pollutants - Wind from SSE
Unit Parameter Model



COMMENTS:	MODEL:	POLLUTANT:	COMPANY NAME:	
Max Receptor at 417946 4600793 50 g/mol MW 10,000 Veh/hr 1,000 g/veh-mi Wind 135 Degrees	CAL3QHC		O'Shea Environmental Associates, Inc.	
	MAX: 144.20	UNITS: ppm		OEA
	LINKS: 5	RECEPTORS: 4767		
	SCALE: 1:146,347 0 — 5 m		DATE: 2/11/2019	PROJECT / PLOT NO.:

CALRoads View - Lakes Environmental Software [C:\Users\...\CALRoads View\CookCo_I294_Unit_225Wind\CookCo_I355_Unit_225Wind\CookCo_I355_Unit_135Wind\CookCo_I355_Unit_135Wind.clv

Appendix E: Visualization of US Traffic



Source: Visualized Department of Transportation Data http://metrocosm.com/map-us-traffic/