Public Health and Climate Change:
Why We Need to Reduce Aromatics in Gasoline

Supporting Information and References

Note: Issues related to aromatics in gasoline are extraordinarily complex, touching many different scientific disciplines – beginning with petroleum refining and combustion science, extending through air pollution chemistry and transport, and ending with toxicology, epidemiology, and life-cycle analysis of greenhouse gas emissions. The overall story is simple and clear – the use of these toxic chemicals in gasoline is causing great harm to public health and the environment – but the elements of the argument are technical and require documentation to be credible. This supporting paper is intended to walk through and expand on the steps of the argument, noting the source of each statement with Internet links, enabling the reader to review them independently. Comments are clearly noted as such.

Outline

I. Emissions from the use of toxic chemicals in gasoline – aromatic hydrocarbons – are causing thousands of premature deaths annually in the United States and harming the cognitive development of children.

1. The effect on public health in brief

a. Incomplete combustion of the aromatics in gasoline (comprising 20% of every gallon) results in tailpipe emissions of fine particles. Inhalation of such particles from fossil fuel combustion is the leading cause of premature death in the world, killing more than 8 million people annually.[1]

b. A recent study found that reducing the smallest (ultrafine) particles without simultaneously limiting organics from automobile emissions "is ineffective and can even exacerbate the problem."[2]

c. Once inhaled, ultrafine particles reach the deepest part of the lungs and enter the bloodstream, where they can cross biological membranes, even the placental barrier, and reach the brain.[3] [4] [5]

d. Not all particles are alike – some may be benign, while others are clearly toxic. Among the worst are polycyclic aromatic hydrocarbons (PAHs), which mix and combine with other gasoline emissions to persist over longer times and distances than previously thought possible.[6]

e. Fetal exposure to extremely low levels of PAHs – levels that are common in dense urban environments – has been associated with developmental delay at age 3 years and reduced IQ at age 5 years, similar to the effects reported for children with elevated concentrations of lead in their blood.[7]

2. Aromatics

a. Aromatics are hydrocarbons built around one or more benzene rings. Often referred to by the acronym BTEX, they include not just benzene itself, a known carcinogen, but also toluene, ethylbenzene, xylenes, and other compounds similar to benzene in their behavior in the environment.[8] People are exposed to BTEX primarily through emissions from motor vehicles and cigarette smoke.[9]

b. Aromatics are derived from petroleum during the refining process and blended into gasoline to increase octane. Their use increased dramatically during the 1980s when the previously used additive, tetraethyl lead, was phased out due to health concerns.[10] [11]

   i. Octane is needed in gasoline to prevent premature combustion of the fuel mixture ("knock"), which can damage engines.[12]

   ii. The level of aromatics in gasoline is capped at 25% in regions that are required to use reformulated gasoline (areas that have high levels of ozone pollution, roughly 30% of the U.S. market).[13] On average, aromatics comprise 20% of the gasoline sold in the U.S.[14] Levels elsewhere (e.g., in Europe and China) have been as high as 40%, worsening air pollution and public health in those regions.[15]

   iii. In the decade from 1997 to 2006 aromatics made up roughly 25% of the U.S. gasoline pool. That level fell to 20% over the next 10 years[16] as ethanol's share

of the market rose from 3% to nearly 10%. This 20% level equates to 25.3 billion gallons of aromatics used in cars and light trucks per year.[17]

iv. Aromatics have a much higher ratio of carbon to hydrogen than other typical hydrocarbons do, driving up the carbon content of gasoline and producing higher greenhouse gas emissions.[18]

v. Aromatics contribute about 10% of global anthropogenic emissions of non-methane organic gases (NMOG), the major source being car exhaust from gasoline-powered vehicles.[19]

vi. Aromatics are also responsible for an estimated 30-40% of the ozone and other photooxidants in urban atmospheres, making them the most important class of hydrocarbons with regard to photochemical ozone formation.[20]

c. The BTEX chemicals are characterized as hazardous air pollutants "known or suspected to cause cancer or other serious health or environmental effects." They are identified as mobile source air toxics and formed in four ways, of which the first two are most pertinent. According to EPA:[21]

i. "First, some air toxics are present in fuel and are emitted to the air when it evaporates or passes through the engine as unburned fuel. Benzene, for example, is a component of gasoline. Cars emit small quantities of benzene in unburned fuel, or as vapor when gasoline evaporates.

ii. "Second, mobile source air toxics are formed through engine combustion processes. A significant amount of automotive benzene comes from the incomplete combustion of compounds in gasoline such as toluene and xylene that are chemically very similar to benzene." *(emphasis added)*

d. Gasoline-powered vehicles accounted for 69% of all U.S. emissions of single-ring aromatic hydrocarbons, based on source-specific speciation in the 2005 National Emissions Inventory.[22]

3. Emissions from aromatics: Particulate matter (PM) and ultrafine particles (UFPs)

a. When a fuel is burned in a vehicle, its molecules break apart and create particulate matter (PM).[23] PM is usually characterized according to its size – in three categories:

i. Some particles, such as dust, dirt, soot, or smoke, are large or dark enough to be seen with the naked eye. These larger particles (2.5 to 10 micrometers in diameter) are called PM_{10} and are mostly derived from soil and sea salts. Fine particles ($PM_{2.5}$, 0.1 to 2.5 micrometers in diameter) and ultrafine particles (UFPs, less than 0.1 micrometer) are predominantly derived from combustion of fossil fuel.[24]

ii. Exposure to $PM_{2.5}$ from fossil fuel combustion was recently shown to be the leading cause of premature death in the world, killing more than 8 million people annually[25] – double the previous estimate – based on a new risk assessment model that found a higher mortality rate for long-term exposure to fossil fuel emissions, including at lower concentrations.[26]

iii. EPA recently announced that it will reconsider its national standards for $PM_{2.5}$, stating: "The strong body of scientific evidence shows that long- and short-term exposures to fine particles ($PM_{2.5}$) can harm people's health, leading to heart

attacks, asthma attacks, and premature death. Large segments of the U.S. population, including children, people with heart or lung conditions, and people of color, are at risk of health effects from $PM_{2.5}$."[27]

1. Children's exposure to air pollution is of special concern because their immune system and lungs are not fully developed.[28]
2. Long-term exposure to $PM_{2.5}$ has also been associated with a large increase in the COVID-19 death rate.[29]

iv. As EPA noted, "While some PM is emitted directly from sources such as construction sites, unpaved roads, fields, smokestacks or fires, most particles form in the atmosphere as a result of complex reactions of chemicals such as sulfur dioxide and nitrogen oxides, which are pollutants emitted from power plants, industrial facilities and vehicles."[30]

1. A recent General Motors study found that nearly 96% of the PM emissions from gasoline are caused by the aromatics in the fuel. Due to an increase in heavy aromatics in the U.S. gasoline pool in the last three years, the gasoline particulate index has increased by more than 30% since 2016 and now is worse than in the EU and China. The authors observed: "Fuel quality improvements are not only important for new vehicles, which are designed for it, but also will benefit the whole fleet of legacy vehicles in the market and off-highway engines."[31]

v. Ultrafine particles (UFPs) are so small that they can only be detected with an electron microscope, and they are more usefully measured by particle number, not mass. They comprise more than 80% of the particles in urban air but are a negligible fraction of $PM_{2.5}$ mass.[32]

1. Studies have shown associations between UFPs and increased asthma symptoms, cardiovascular disease markers, and decreased cognitive function.[33]
    a. In a recent U.S. study, prenatal UFP exposure was linked to asthma development in children: Children whose mothers were exposed to high levels of UFPs during pregnancy were four times more likely to develop asthma than those whose mothers were exposed to lower levels – roughly the difference between a quiet street and a busy road. Most of the diagnoses occurred just after three years of age, and overall 18% of the infants developed asthma. The researchers took account of other factors, including the age of the mothers and obesity, as well as other air pollutants. [34] [35]
2. UFPs contain large amounts of toxic components, and their adverse health effects potential would not be predicted from their mass alone. Particle number, surface area, and chemical composition are more important than mass as a health-relevant metric.[36]
3. There is a growing concern in the public health community about the contribution of UFPs to human health. Despite their modest mass and size, they dominate in terms of the number of particles in the ambient

air. A particular concern about UFPs is their ability to reach the most distal lung regions (alveoli) and circumvent primary airway defenses. Moreover, UFPs have a high surface area and a capacity to adsorb a substantial amount of toxic organic compounds. Harmful systemic health effects of PM_{10} or $PM_{2.5}$ are often due to the UFP fraction.[37]

5. The ability of inhaled particles to be captured within the human body, called the deposition efficiency, is a function of particle size, with the particle deposition efficiency rapidly increasing as the particles become smaller and smaller.[38]
6. UFPs can cross biological membranes, and their mobility within the body is thought to be high. There is considerable evidence to show that inhaled UFPs can gain access to the bloodstream and are then distributed to other organs in the body. They can even cross the placental barrier.[39]
7. UFPs have been shown to directly translocate to the brain along the olfactory nerves. In addition, they can pass intact into cells, where they can have direct access to cytoplasmic proteins and organelles – for example, the mitochondria impacting the respiratory chain and DNA in the nucleus – enhancing the toxic potential of these particles.[40]
8. Results indicating that particles may contribute to the overall oxidative stress burden of the brain are particularly troublesome, as these long-term health effects may accumulate over decades.[41]

vi. Research also suggests that the introduction of excessive UFPs into the atmosphere results in diverse unwanted side effects, such as changes in the distribution and intensity of rainfall, causing either drought or flooding in extreme cases. Such drastic climate change affects the global hydrological cycle and thereby affects global public health both directly and indirectly.[42]

vii. In most urban environments, on-road vehicles are the primary source of UFP emissions.[43] These areas observe a peak in UFPs in the morning during rush hour associated with motor vehicle emissions and a second peak during the afternoon, enhanced during the summer, associated with photochemistry, or one slightly later in the afternoon due to rush hour traffic that is enhanced during cooler conditions.[44]

viii. An important recent study co-authored by Nobel Prize winner Mario Molina found "remarkable formation of UFPs from urban traffic emissions":[45]

1. Photooxidation of vehicular exhaust yields abundant UFP precursors, and organics dominate formation of UFPs under urban conditions. Measurements of gaseous species inside the chamber showed high levels of aromatics, including toluene and C8 and C9 aromatics.[46]
2. The authors concluded: "Recognition of this source of UFPs is essential to assessing their impacts and developing mitigation policies. Our results imply that reduction of primary particles or removal of existing particles without simultaneously limiting organics from automobile

emissions is ineffective and can even exacerbate this problem."[47] *(emphasis added)*

b. The newest generation of efficient engine technology, gasoline direct injection (GDI), increases public exposure to gasoline PM, and thus to UFPs, including PAHs.[48]
    i. Vehicle exhaust, in particular that of gasoline direct injection (GDI) engines, contains copious amounts of particles in the size ranges with high deposition efficiency.[49] GDI engines emit UFPs and PM at levels comparable to diesel engines that do not use diesel particulate filters.[50] [51]
        1. Unlike conventional port fuel injection engines, which mix fuel and air prior to injection into the engine cylinders, GDI technology involves spraying the fuel directly into the cylinders, allowing for higher compression ratios – which enable higher combustion efficiencies, enhanced fuel economy and reduced CO_2 emissions, by up to 14%. However, similar to diesel engines, the direct injection of fuel in GDI engines creates fuel-rich pockets near the injection zone, conducive to formation of carbonaceous PM, especially black carbon. GDI engines emit larger amounts of black carbon than conventional engines, as has been confirmed by several laboratory studies.[52]
    ii. GDI was used in fewer than 3% of vehicles as recently as model year 2008 but was projected to be used in more than 55% of vehicles in model year 2020.[53]
        1. This shift to GDI engines is predicted to nearly double annual deaths in the U.S. from gasoline-vehicle particulate emissions – according to one estimate, from 855 to 1,599 deaths a year.[54]
    iii. Emissions from GDI engines can be mitigated by changes in operating parameters,[55] by the addition of gasoline particulate filters[56] (both with potential costs to vehicle efficiency), or by a reduction in aromatic content.

c. There is a strong link between PM emissions from GDI engines and the composition and properties of the gasoline, chiefly the aromatic content of the fuel: High levels of aromatics lead to a higher level of PM emissions.[57]
    i. Aromatic compounds are harder to evaporate and slower to decompose than other hydrocarbons. Aromatics also may decompose into compounds such as acetylenes which serve as precursors for the formation of a benzene ring.[58]
    ii. High levels of aromatic components in fuel have been conclusively shown to increase PM emissions measured by particle number, an aromatic ring being an early stage of the fundamental particulate formation process.[59]

4. Emissions from aromatics: Secondary organic aerosol (SOA)

a. Organic aerosol is a major component of fine particle pollution. Primary organic aerosol (POA) is directly emitted from fossil fuel combustion and other sources, while secondary organic aerosol (SOA) is formed from the oxidation of these emissions in the atmosphere.[60]
    i. Tailpipe emissions from on-road gasoline vehicles are an important source of SOA in urban environments, where SOA concentrations often exceed POA levels. For most vehicles, SOA formation exceeds POA emissions after a few

hours of atmospheric oxidation. Controlling SOA precursor emissions is necessary to reduce human exposure to fine particulate matter.[61]

ii. A study of SOA formation during a severe photochemical smog event in Los Angeles found that exhaust from gasoline engines represented the single-largest anthropogenic source of SOA, and SOA in turn has been shown to be a large fraction, if not the largest, of gasoline vehicular PM.[62]

b. According to EPA's 2011 National Air Toxics Assessment, secondary formation is the largest contributor to cancer risks nationwide, accounting for 47% of the risk. On-road mobile sources contribute the most cancer risk from directly emitted pollutants (about 18%) and the most to non-cancer risks (34%).[63]

i. A recent study found higher toxicity in combustion aerosols than non-combustion aerosols, with emissions from vehicle engine exhaust scoring higher on overall toxicity than even those from coal combustion.[64]

c. EPA said in 2005: "Aromatic compounds … are considered to be the most significant anthropogenic SOA precursors and have been estimated to be responsible for 50 to 70% of total SOA in some airsheds. … The experimental work of Odum and others showed that the secondary organic aerosol formation potential of gasoline could be accounted for solely in terms of its aromatic fraction."[65] *(emphasis added)*

i. The effect of aromatics on SOA does not seem to be linear: Increasing the level of aromatics in test fuels by less than 30% (from 28.5% to 36.7%) was shown to cause a 3- to 6-fold increase in SOA formation.[66]

d. One study estimated that SOA from aromatics in gasoline is responsible for 3,800 annual premature deaths and annual social costs of $28.2 billion in 2006 dollars.[67]

i. Those mortality numbers can be compared to the impact of EPA ozone regulation, a major focus of the Clean Air Act – predicted to reduce premature mortalities by 4,300-7,100 deaths per year.[68]

e. Ozone "forms in the atmosphere through a series of complex, non-linear chemical interactions of precursor pollutants."[69] The cost of ozone regulation has been estimated to be more than $14 billion annually,[70] with benefits of more than $55 billion per year.[71]

i. Many air toxics contribute to ozone formation, especially aromatics, so there is a double benefit to reducing them.[72] However, an EPA assessment of the Clean Air Act found approximately 98% of avoided premature mortalities were due to reductions in PM concentrations, not ozone."[73] [74]

5. Emissions from aromatics: Polycyclic aromatic hydrocarbons (PAHs)

a. Not all particles are alike – some may be benign, while others are clearly toxic. Polycyclic aromatic hydrocarbons (PAHs) are among the worst. EPA has classified seven PAHs as probable human carcinogens.[75]

i. The Occupational Safety and Health Administration has set a limit of 0.2 milligrams of PAHs per cubic meter of air (0.2 mg/m^3).[76]

b. A subset of polycyclic organic matter (POM), PAHs consist of three to seven benzene rings. The PAH family includes more than 100 different compounds of a similar chemical nature, all products of incomplete combustion of organic materials. Among all sources,

vehicular exhaust is the major and common source for PAH air pollution in most urban areas.[77] [78]

c. Complex mixtures of various PAH compounds are spread with the wind in the environment, where their presence poses a risk to human health through ingestion and inhalation. PAHs do not easily degrade in the environment – they undergo long-distance transport and accumulate in aquatic sediment, where some of them pose a threat to aquatic life.[79]
d. PAHs are commonly divided into two categories based on their size. PAHs with two to three fused aromatic rings are considered low molecular weight PAHs, while those with four and more fused rings are high molecular weight PAHs, including the most carcinogenic PAH, benzo[a]pyrene (BaP).[80]
    i. The larger PAHs are of greatest concern for human health due to their recalcitrance to degradation, persistence, bioaccumulation, carcinogenicity, genotoxicity and mutagenicity.[81] Since these high molecular weight PAHs exist almost exclusively on fine particles, they travel deep into the human respiratory system and pose a serious health risk.[82]
    ii. More than 95% of the lung deposition of PAHs is due to fine particles, and ultrafine particles are responsible for 10 times more PAH deposition in the alveolar region than their share of PM mass.[83]
e. Combustion of vehicle fuels appears to be the principal source of inhalation exposure for the larger PAHs, such as BaP, that are associated with particulate matter.[84]
    i. BaP is one of 12 Level 1 priority compounds among the "toxic, persistent and bioaccumulative" chemicals targeted for "virtual elimination" by the Great Lakes Binational Toxics Strategy signed by the U.S and Canada in 1997.[85] It is almost entirely produced by vehicular emissions.[86]
f. Motor vehicles account for as much as 90% of the particle-bound PAH mass in the urban air of major metropolitan areas. Roadway tunnel and dynamometer studies have shown that diesel vehicle emissions are rich in the lower molecular weight PAHs, whereas the higher molecular weight PAHs (of greatest concern for human health) are associated with gasoline vehicle emissions.[87] [88]
    i. In a tunnel study, for example, diesel trucks were the major source of lighter PAHs, whereas light-duty gasoline vehicles were the dominant source of higher molecular weight PAHs, such as BaP. PAH emissions from gasoline were almost entirely ultrafine particles (UFPs).[89]
        1. Only the high molecular weight aromatics markedly affect particle number.[90]
        2. As the molecular weight of a specific PAH increases, the carcinogenicity of PAHs also increases.[91]
        3. A comparison of $PM_{2.5}$ with smaller particles attributed about 86% of the total carcinogenic potency to the PM_1 fraction (particles smaller than 1 micrometer in diameter).[92]
        4. UFPs contain a higher percentage of organic carbon than fine and coarse particles, which is relevant to their biologic potency, and the enhanced biologic potency of UFPs is correlated with the PAH content.[93]

ii. Just as with SOA, the effect of aromatics on PAH formation does not seem to be linear: Increasing the aromaticity of the fuel by 12% to 46% was found to increase PAH emissions by 8 to 74%.[94]

iii. The presence of PAHs has a large effect on SOA formation – increasing mass loadings by factors of two to five, and particle number concentrations, in some cases, by more than a factor of 100.[95]

- **Note:** The effect of aromatics on pollution and human health is thus magnified twice over: Aromatics lead disproportionately to PAH formation, and PAHs lead disproportionately to SOA formation. Worse yet, PAHs hitch a ride on SOA for long distances and weaponize these particles as they travel through the human body.

g. Groundbreaking research at Pacific Northwest National Laboratory (PNNL) has led to new understanding of the process by which PAHs persist and are transported long distances. It was shown that the most carcinogenic PAH, benzo[a]pyrene (BaP) – often used as a marker for PAH content generally – is efficiently bound to and transported with atmospheric particles:

i. In the laboratory, particle-bound BaP degrades in a few hours, but field observations indicate it persists much longer in the atmosphere and is transported far from its sources – increasing its global lung cancer risk as much as fourfold. BaP from East Asia, for example, has been shown to travel thousands of miles over the Pacific Ocean, reaching the west coast of the United States.[96]

ii. When SOA particles are formed in the presence of gas-phase PAHs, their formation and properties are significantly different from SOA particles formed without PAHs: They exhibit slower evaporation kinetics and have higher fractions of non-volatile components and higher viscosities, assuring their longer atmospheric lifetimes. This increased viscosity and decreased volatility act as a shield that protects PAHs from chemical degradation and evaporation, allowing for their long-range transport.[97]

h. Based on numerous experimental studies, PAHs are also widely accepted to be precursors for soot, or black carbon – a major contributor to climate change.[98] [99] Products of toluene combustion (one of the BTEX aromatics) are known precursors of PAHs that are involved in soot formation.[100]

i. Black carbon is considered the second most important human emission in terms of climate forcing; only carbon dioxide (CO_2) has a greater overall effect. The short-term (20-year) global warming potential per ton of black carbon is 3200 times that of CO_2.

1. Black carbon emissions associated with the shift to GDI engines will lead to increased warming over the U.S., especially in urban regions.[101]

ii. However, black carbon is rapidly removed from the atmosphere by deposition, and its atmospheric concentrations respond quickly to reductions in emissions. Reductions in black carbon are thus an attractive near-term mitigation strategy to slow the rate of climate change.[102]

6. **EPA's modeling – Part 1**
    a. EPA has long acknowledged its modeling shortcomings in this area. Noting that "SOA continues to be a significant topic of research and investigation," it said in 2005: "Despite significant progress that has been made in understanding the origins and properties of SOA, it remains the least understood component of $PM_{2.5}$."[103]
        i. Atmospheric models have been found to underestimate SOA emissions by an order of magnitude or more when applied in and downwind of urban areas/polluted regions.[104] [105] *(emphasis added)*
    b. EPA's summary of a 2015 workshop on UFPs contained this admission, based on the PNNL research described above, unpacking the implications of its knowledge gap:
        i. "[SOA] particles play an important role in air quality but for many years available atmospheric models were not able to predict SOA formation. The main issue was the fact that all models relied on the assumptions that SOA particles were well-mixed low viscosity solutions and maintained equilibrium with the gas-phase by rapid mixing in the condensed phase with evaporation and condensation. Recent studies using the multidimensional characterization approach demonstrated that these assumptions were wrong and that SOA particles must be viscous semi-solid. These studies showed also that there is a synergetic effect between PAHs and SOA since PAHs trapped inside the SOA particles slow down SOA evaporation and increase SOA yield and lifetime. This can explain the long-range transport of toxic compounds like PAHs and other persistent pollutants. In conclusion, a new SOA paradigm has been developed."[106] *(emphasis added)*

    - **Note:** The modeling that EPA has used to assess and regulate SOA emissions was thus based on erroneous assumptions and completely missed the scale of the problem. The significance of this failure is heightened by the finding in the 2011 National Air Toxics Assessment that secondary formation is the largest contributor of all sources to cancer risks nationwide, accounting for 47% of the risk.[107]

    c. EPA sets air standards for $PM_{2.5}$ based on mass,[108] when the more important measure of health risk may be the number of extremely lightweight ultrafine particles.
        i. This is particularly important because gasoline direct-injection (GDI) engines (the new automotive norm) emit a higher level of PM emissions measured by particle number than the prior technology, port fuel injection engines.[109]
    d. EPA's assessment of the health risks of PAHs, as reflected in its modeling protocols, is also based on a limited sample of the PAH universe. This approach understates the total carcinogenic potency of PAHs by an estimated 85.6%.[110]

7. **Health effects of PAH exposure**
    a. Toxic air pollutants can affect health and functioning over the course of life by launching a trajectory of adverse effects related to the initial physical or developmental impairment, and/or by "seeding" latent disease that becomes evident only in later life.[111]

b. In cells UFPs have been found to induce heme oxygenase-1 (HO-1) expression, a sensitive marker for oxidative stress, directly correlated with the high organic carbon and PAH content of UFPs. Oxidative stress is associated with numerous diseases, including cardiovascular disease, hypertension, and diabetes.[112]
c. Fetal exposure to PAHs, as measured by prenatal air monitoring for the marker PAH benzo[a]pyrene during the third trimester of pregnancy, was assessed in a long-term observational epidemiological study in New York. Exposure levels were characterized relative to a median of 2.66 nanograms per cubic meter (ng/m^3) – that is, 100,000 times less than the OSHA air standard of 0.2 mg/m^3.[113] (A nanogram is one-millionth of a milligram.)
    i. Fetal exposure above the median was associated with developmental delay at age 3 years and reduced IQ at age 5 years, as well as increased anxiety and depression, possibly by interfering with knowledge acquisition or slowing cognitive processing.[114] The observed decrease in full-scale IQ is similar to that reported for children with elevated concentrations of lead in their blood.[115]
        1. The effects of lead exposure include neurological effects in children and cardiovascular effects (e.g., high blood pressure and heart disease) in adults. Infants and young children are especially sensitive to even low levels of lead, which may contribute to behavioral problems, learning deficits, and lowered IQ.[116]
    ii. DNA adducts are a form of DNA damage caused by attachment of a chemical entity to DNA. Adducts that are not removed by the cell can cause mutations that may give rise to cancer.[117] The formation of PAH-DNA adducts has been widely studied in experimental models and has been documented in human tissues.[118] Higher levels of PAH-DNA adducts found in umbilical cord blood were associated with reduced scores on neurocognitive tests.[119]
d. A long-term study in California also found an association between exposure to airborne PAHs during the last 6 weeks of pregnancy and early preterm birth – with average exposure at the extremely low level of 3.6 ng/m^3.[120]
    i. Preterm birth is a predictor of infant mortality and later-life morbidity. Despite recent declines, the rate of preterm birth remains high in the U.S. Research increasingly suggests a possible relationship between a mother's exposure to common air pollutants, including $PM_{2.5}$ and preterm birth of her baby. [121]

II. Thirty years ago Congress required EPA to control these hazardous air pollutants to the greatest degree achievable, yet aromatics still comprise a fifth of the nation's gasoline supply, amounting to more than 25 billion gallons a year.

1. EPA's response to a legislative mandate

a. The Clean Air Act Amendments of 1990 contained the following requirement, codified as Section 202(l)(2) of the Clean Air Act, *Mobile source-related air toxics - Standards*: "Within 54 months after November 15, 1990, the [EPA] Administrator shall … promulgate (and from time to time revise) regulations … containing reasonable requirements to control hazardous air pollutants from motor vehicles and motor vehicle fuels. The

regulations shall contain standards for such fuels or vehicles, or both, which the Administrator determines reflect the greatest degree of emission reduction achievable through the application of technology which will be available, taking into consideration the standards established under subsection (a), the availability and costs of the technology, and noise, energy, and safety factors, and lead time."[122] *(emphasis added)*

i. Congress made its intent clear by specifically naming the BTEX aromatics (benzene, toluene, ethylbenzene, and xylenes), along with polycyclic organic matter, as hazardous air pollutants.[123]

ii. Additionally, in the section requiring reformulated gasoline in areas with high summertime ozone levels, the statute requires "the greatest reduction in … emissions of toxic air pollutants (during the entire year) achievable through the reformulation of conventional gasoline" – with the term "toxic air pollutants" specifically defined as including polycyclic organic matter (POM) for this subsection.[124]

b. In the 30 years since the law was enacted, EPA has issued specific regulations on the subject of mobile source air toxics (MSATs) only twice – putting modest limits on benzene emissions in 2001 and on the benzene content of gasoline in 2007, but largely deferring action on the others.

i. The 2001 rule did list the BTEX aromatics as mobile source air toxics and noted that mobile sources accounted for more than 75% of total national emissions in each instance. Also listed was polycyclic organic matter: A group of seven PAHs, "which have been identified by EPA as probable human carcinogens" – including BaP – were used as surrogates for the larger group of POM compounds. Mobile sources were said to account for only 6% of total national emissions – but as measured by mass, not particle number.[125]

c. Congress reiterated its 1990 mandate in the Energy Policy Act of 2005: "Not later than July 1, 2007, the [EPA] Administrator shall promulgate final regulations to control hazardous air pollutants from motor vehicles and motor vehicles fuels ... as authorized under section 202(l) of the Clean Air Act."[126]

i. EPA issued its 2007 rule in response to this congressional directive. It acknowledged that "Recent studies have found that maternal exposures to PAHs in a population of pregnant women were associated with several adverse birth outcomes, including low birth weight and reduced length at birth, as well as impaired cognitive development at age three."[127]

1. But EPA took no action, saying that, according to its model, emissions of polycyclic organic matter "correlate directly with VOC emissions" and thus would decline as VOC emissions decline[128] – failing to anticipate the contrary effect of new GDI engine technology, noted above.

ii. In proposing the rule, the agency also acknowledged "limited data that suggest that aromatic compounds (toluene, xylene, and benzene) react photochemically in the atmosphere to form secondary particulate matter (in the form of secondary organic aerosol (SOA)), although our current modeling tools do not fully reflect this."[129] *(emphasis added)*

1. The rule's Regulatory Impact Analysis said: "The issue of SOA formation from aromatic precursors is an important one to which EPA and others are paying significant attention. Due to the large contribution of mobile source emissions to overall aromatic levels in the atmosphere, this issue is a crucial one for assessing what further reductions are possible in mobile source PM."[130] *(emphasis added)*

iii. In the final rule, EPA said: "There may be compelling reasons to consider aromatics control in the future, especially regarding reduction in secondary $PM_{2.5}$ emissions, to the extent that evidence supports a role for aromatics in secondary $PM_{2.5}$ formation. Unfortunately, there are limitations in both primary and secondary PM science and modeling tools that limit our present ability to quantitatively predict what would happen for a given fuel control. … [M]ore work is underway on how fuel aromatics, including toluene, affect secondary PM formation, and how aromatics control should be incorporated into air quality predictive models. … Thus, we have concluded that additional aromatics control for MSAT purposes is not warranted at this time."[131] *(emphasis added)*

1. The final rule stated, in summary: "EPA believes that the emission reductions from the standards finalized today for motor vehicles and their fuels, combined with the standards currently in place, represent the maximum achievable reductions of emissions from motor vehicles through the application of technology that will be available, considering costs and the other factors listed in section 202(l)(2)."[132] *(emphasis added)*

- **Note:** EPA's conclusion that it had required "the maximum achievable reductions" was wrong then and is even more clearly wrong today, as shown in Section III, below. Additionally, more than 13 years after issuing the 2007 rule, EPA has still not taken action on "assessing what further reductions are possible in mobile source PM" or on "how aromatics control should be incorporated into air quality predictive models."

d. EPA missed another opportunity to act in 2014, in its rule on Tier 3 Motor Vehicle Emission and Fuel Standards, which it said would result in "significant reductions in pollutants such as ozone, particulate matter, and air toxics."[133]

i. EPA acknowledged that "the majority of Americans continue to be exposed to ambient concentrations of air toxics at levels which have the potential to cause adverse health effects. … According to the National Air Toxics Assessment (NATA) for 2005, mobile sources were responsible for 43% of outdoor toxic emissions and over 50% of the cancer risk and noncancer hazard associated with primary emissions. Mobile sources are also large contributors to precursor emissions which react to form secondary concentrations of air toxics."[134]

ii. Yet the agency took no direct action to reduce air toxics or even to estimate the benefits of the action it did take: "While there would be impacts associated with reductions in air toxic pollutant emissions that result from the final standards, we do not attempt to quantify and monetize those impacts…. This is primarily because currently available tools and methods to assess air toxics risk from

mobile sources at the national scale are not adequate for extrapolation to incidence estimations or benefits assessment."[135] *(emphasis added)*

iii. The Tier 3 rule lowered the maximum sulfur content in gasoline to avoid the poisoning of emissions catalysts and make emission control systems more effective,[136] but the sulfur reduction produced no benefit for PM emissions: "Unlike the gaseous pollutants, there was no effect of sulfur level found for PM. … As a result, sulfur would not be expected to have a significant effect on directly-emitted PM (other than very small amounts of sulfate)."[137]

1. In fact, the rule may have had a contrary consequence: For many refiners, operating strategies that reduce sulfur also reduce octane. According to one analysis, "the majority of refiners are meeting the regulations by increasing hydrotreating severity," which negatively impacts octane – potentially leading to increased use of aromatics to compensate.[138]

e. Most recently, in December 2020 EPA issued a "Fuels Regulatory Streamlining" rule that relieved refineries of their responsibility to report regularly on the aromatics levels in reformulated gasoline (approximately 30% of the national gasoline pool). An industry-led annual sampling program will be used instead. Refineries also are no longer required to estimate emissions of air toxics, including polycyclic organic matter.[139]

2. EPA's modeling – Part 2

a. EPA's MOtor Vehicle Emission Simulator (MOVES) is a modeling system that estimates emissions for mobile sources at the national, county, and project level for criteria air pollutants, greenhouse gases, and air toxics. Its use is required for the development of State Implementation Plans to reduce air pollution in areas that do not meet National Ambient Air Quality Standards.[140]

i. In 2014 EPA updated the MOVES model to incorporate new emissions factors for ethanol blends. These changes were based on a laboratory analysis that used "match blending" to simulate the performance of various fuel formulas. This approach was fundamentally flawed:

1. Aromatics were added (above the 25% legal limit for reformulated gasoline) to match certain parameters of fuels that had less ethanol. The resulting degradation of emissions was primarily caused by the added aromatics but was incorrectly blamed on the ethanol.[141]
2. This mistake caused the MOVES model to predict incorrectly elevated emissions factors for ethanol blends. For example, smog-forming nitrogen oxides (NO_x) have been shown in the real world to decrease as the percentage of ethanol increases, but the MOVES model predicts higher NO_x emissions for ethanol blends.[142]

ii. Emissions tests by the U.S. Department of Energy have confirmed that "even though ethanol is more catalytically reactive than other gasoline components, ethanol will likely neither help nor hinder compliance with NOx, non-methane organic gases (NMOG), and CO regulations in realistic fuel blends."[143]

iii. Despite repeated calls to fix this clear error, EPA has not done so.

III. Cleaner burning substitutes are readily available and affordable and should be phased in as quickly as practicable.

1. Ethanol and vehicle performance

a. Like aromatics, alcohols such as ethanol have a much higher octane rating than base refinery gasoline. Increasing ethanol levels raises the octane rating of finished gasoline. In effect, aromatics and ethanol compete for the octane enhancement market.

b. Higher octane enables greater engine efficiency and improved vehicle performance through higher compression ratios and/or more aggressive turbocharging and downsizing – also facilitated by ethanol's cylinder 'charge cooling' effect due to its high heat of vaporization.[144] Raising the engine's compression ratio from 10:1 to 12:1 could increase vehicle efficiency by 5-7%.[145] [146]

   i. To increase octane enough to achieve these efficiency gains (i.e., to a "premium" rating of 94 AKI (anti-knock index) at the gas pump), there are two principal options – aromatics or alcohols.[147]

   ii. Since 2016, researchers at nine national laboratories working with the U.S. Department of Energy's Co-Optimization of Fuels & Engines initiative (known as Co-Optima) have explored how simultaneous innovations in fuels and engines can boost fuel economy and vehicle performance, while reducing emissions.[148]

      1. The initiative identified 10 candidate fuels from four chemical families – alcohols, olefins, furans, and ketones – with the greatest potential to increase vehicle efficiency. Seven of them were alcohols.[149]
      2. A team at Oak Ridge National Laboratory found that intermediate alcohol-gasoline blends (particularly a 30% ethanol blend, or E30) "exhibit exceptional antiknock properties and performance beyond that indicated by the octane number tests,"[150] and that engine and vehicle optimization could offset the reduced fuel energy content of such blends and likely reduce vehicle fuel consumption and tailpipe CO_2 emissions.[151] [152]
      3. The use of E30 in one test vehicle enabled a 13:1 compression ratio, reducing CO_2 emissions by 6-9%.[153]

c. A shift from E10 to E30 would displace an estimated 40% of the BTEX aromatics[154] – the most carbon-intensive fraction of gasoline.[155]

   i. The addition of ethanol also hinders the formation of soot precursors, including PAHs, in turn reducing PM emissions.[156]

   ii. Ethanol does not contribute to SOA or PAH formation.[157]

d. A 2012 study by Ford engineers examined the influence of ethanol on PM emissions from vehicles with GDI engines. It found a very strong reduction in particle emissions by mid-level ethanol blends above E20. In other words, there was a modest benefit from lower-level blends and a dramatic improvement from mid-level blends: "When the ethanol content increases to >30%, there is a statistically significant 30%-45% reduction in PM mass and number emissions.[158]

- **Note:** Automakers could quickly adapt to higher-level blends and meet consumer preference for increased engine power and efficiency with a cleaner, often cheaper fuel.

In a recent letter, the Alliance for Automotive Innovation, a group of automakers that produce nearly 99% of the new light-duty vehicles sold in the U.S., said:[159]

> [A]s automakers invest significantly in the transition to expanded vehicle electrification, the auto industry is also continuing to invest in vehicle improvements that increase fuel economy and reduce greenhouse gases in internal combustion engine vehicles. Many of the technologies being used to make these improvements can be enhanced or complemented with the use of high octane, low carbon liquid fuels. These fuels would simultaneously support vehicle performance, including fuel economy, and further reduce greenhouse gas emissions during vehicle use. Such benefits would be realized by new and existing internal combustion engines and therefore should be encouraged as additional solutions as soon as possible to maximize environmental benefits across the fleet. Given the timespan over which combustion technology will continue to be sought by new car shoppers, and the timespan that those vehicles will remain in the field, low carbon liquid fuels are an increasingly important technology pathway to help achieve carbon reductions while the electric vehicle market continues to grow. *(emphasis added)*

e. Ethanol has a long history as a transportation fuel. Henry Ford built his very first car to run on what he called farm alcohol. In 1921 Thomas Midgley, the same engineer who later developed tetraethyl lead for a General Motors subsidiary, drove to a meeting of the Society of Automotive Engineers using a gasoline blend with 30% ethanol. The benefits, he said, included "clean burning and freedom from any carbon deposit … [and] tremendously high compression under which alcohol will operate without knocking. … Because of the possible high compression, the available horsepower is much greater with alcohol than with gasoline."[160]
f. The proven technology used by today's ethanol industry enables rapid scale-up. The industry tripled its production capacity in just four years – from 4.4 billion gallons a year in 2005 to 14.5 billion in 2009.[161] U.S. ethanol production capacity today is 17.4 billion gallons.[162]
    i. The transportation fuel infrastructure has also adapted to the increased use of ethanol in cars and light trucks. As 10% ethanol blends became the market's dominant fuel, refiners reduced their use of aromatics and lowered the octane content of their blendstocks.[163] [164]
    ii. New gas pumps are now certified for mid-level ethanol blends.[165]
g. EPA has determined that, for vehicles from model year 2001 on, "E15 will not cause or contribute to a failure to achieve compliance with the emissions standards to which these vehicles were certified over their useful lives."[166]
    i. Real-world experience indicates that higher-level blends such as E30 are, like E15, also harmless to existing vehicles. In Watertown, SD, dynamometer testing and on-road driving experience have shown that conventional vehicles using E30 benefit from greater horsepower and torque, providing better vehicle performance, drivability, and increased power. They also experience no loss in fuel economy (despite ethanol's lower energy content) due to engine sensors

that can recognize the higher octane and adjust spark ignition timing for greater efficiency.[167]

1. The State of Nebraska recently conducted similar tests with 50 conventional vehicles and found that "E30 had no observable negative effect on overall vehicle performance."[168]

h. Brazil has been the largest laboratory in the world for ethanol as an automotive fuel, dating back to the launch of the National Alcohol Program in 1975. Ethanol has made up at least 20% of the standard gasoline blend in Brazil almost continuously since 1984.[169] Currently the standard national blend is set at 27%, and one third of the fleet is capable of operating on ethanol alone.[170]

i. The city of São Paulo, which had a traditional problem with smog and toxic emissions from automobiles, saw significant improvements in air quality due to ethanol use.[171] São Paulo is among the top 10 urban concentrations in the world, but in 2019 it fared better than 1200 other cities globally in terms of particulate air pollution.[172]

1. The use of high levels of ethanol in gasoline made it unnecessary to produce gasoline with high aromatics content. Nor did it result in ambient aldehyde levels that might bring significant risks to the population.[173] (Aldehydes such as acetaldehyde and formaldehyde are byproducts of ethanol combustion but, as noted below, can be easily controlled by conventional emissions technology.)

2. Ethanol and climate change

a. A 2017 assessment by the consulting firm ICF concluded that life-cycle greenhouse gas (GHG) emissions associated with producing corn-based ethanol in the United States, using today's practices in a typical natural gas-powered refinery, are almost 43% lower than those of gasoline on an energy-equivalent basis.[174] [175]

i. This estimate is consistent with more than 15 years of life-cycle analysis at Argonne National Laboratory, recently reaffirmed in a retrospective analysis.[176] [177] It is also more than twice as large as the 21% reduction predicted by EPA in its 2010 life-cycle analysis for ethanol produced by an average natural gas-fired plant in 2022.[178]

ii. A recent "state-of-the-science review" by the consulting firm Environmental Health & Engineering yielded a "central best estimate of carbon intensity for corn ethanol" that was 46% lower than for gasoline.[179]

iii. Another way to assess the value of ethanol is to calculate its net gain in energy content. On that point, a recent USDA report concluded that a corn ethanol plant using conventional fossil fuel power and electricity "produces slightly more than twice the energy in the form of ethanol delivered to customers than it uses for corn, processing, and transportation."[180]

iv. California's Low Carbon Fuel Standard (LCFS) has demonstrated the impact of market-based price incentives for environmental performance. To gain credits under the LCFS, ethanol refineries have steadily reduced their carbon scores

through increased production efficiencies, most notably by shifting from coal to natural gas as a process fuel.

1. For the purpose of credits under the LCFS, corn ethanol on average is currently rated as 30% better than its gasoline blendstock.[181]
2. LCFS credits have led to an annual average gain in E85 sales of nearly 39% over the last 10 years.[182]
3. Providing credit for soil carbon sequestration under the LCFS would incentivize farmers to employ improved conservation practices. Such practices would reduce ethanol's carbon footprint further – as much as 70% lower than gasoline, the ICF report found.[183]
4. In 2020 the House Select Committee on the Climate Crisis recommended that Congress develop a national LCFS reflecting "the best-available science about the carbon intensity of fuel production, farming practices, land use changes, and crop productivity." Such a standard, the report said, should reward producers that use "climate-smart practices that reduce carbon emissions, store soil carbon, and reduce nitrous oxide emissions."[184]

v. The carbon dioxide produced by the ethanol process is extremely pure – making it easier to capture and reuse than CO_2 from a power plant. Ethanol giant Archer Daniels Midland is capturing CO_2 from its processing facility in Decatur, IL, and storing it permanently underground – another step that could lower ethanol's carbon footprint.[185] However, this process was made possible by a $141 million federal grant and is not yet justified economically.[186]

1. A recently announced project will capture CO_2 from several biorefineries in the Midwest for geologic storage – of up to 10 million tons annually – in underground saline aquifers in North Dakota.[187]
2. Recently scientists at Argonne National Laboratory reported discovery of a new electrocatalyst that converts CO_2 and water into ethanol with very high energy efficiency, high selectivity, and low cost. If proven at scale, this could enable the production of ethanol from CO_2 emitted by industrial processes of all kinds.[188]

b. U.S. consumption of gasoline adds roughly 1 billion metric tons of the most significant greenhouse gas, carbon dioxide (CO_2), to the atmosphere per year.[189]

i. Based on current consumption rates of gasoline, increasing vehicle fuel economy by 7% with the higher octane of an E30 blend would reduce annual U.S. emissions by 70 million metric tons per year.[190]

ii. Reducing the share of aromatics in gasoline by 40% – with E30 fuel that is 40% less emitting – would reduce U.S. emissions by another 32 million metric tons per year.[191]

iii. GHG emissions from oil refineries would also fall, due to reduced demand for their most intensively refined products. Oil refiners could produce blendstocks for E30 gasoline at a modest additional cost of 1-2 cents per gallon. Reduced refinery throughput and intensity would reduce refinery CO_2 emissions and crude oil consumption.[192]

1. One assessment found that refinery GHG emissions would decline by 12% to 27% for various E30 cases, due to both lower crude oil throughput and differences in the severity of refining operations.[193] Since the refinery sector emits 180 million metric tons per year,[194] that would mean a further reduction in U.S. GHG emissions of at least 21 million metric tons per year.

iv. Thus, the total reduction in U.S. GHG emissions from adoption of E30 blends – combining fuel economy gains, the replacement of aromatics with a lower-carbon substitute, and the change in refinery operations – would total 123 million metric tons per year. That would be a cut of more than 12% in emissions from light-duty vehicles, which comprise 59% of the emissions from the transportation sector (the source of more GHG emissions than any other sector).[195]

1. Valuing the social cost of those avoided emissions at $25 per ton would imply a benefit of more than $3 billion per year. At the "interim" rate of $51 per ton put forward by the Biden administration in 2021, the benefits would add up to more than $6 billion per year.[196]

v. An aggressive program to increase adoption of electric vehicles is urgently needed to phase out fossil fuels altogether, but even optimistic forecasts recognize that it will take a long time to turn over the U.S. fleet of 250 million light-duty vehicles.[197] (The average age of such vehicles in operation in the U.S. has risen to 12.1 years this year.)[198] Internal combustion engines will still be used in hundreds of millions of vehicles between now and 2050.

1. California is in the vanguard of the transition to electric vehicles in the U.S., with a newly announced goal of limiting new-car sales in 2035 to zero-emission vehicles.[199] But under the state's LCFS program to date (since 2011), ethanol has reduced GHG emissions by nearly three times more than electricity. As more electric vehicles enter the market, that ratio is dropping sharply, but even for the last 12 months reported (through December 2020), ethanol reduced GHG emissions by one third more than electricity – despite being limited almost entirely to E10 blends.[200]

3. The use of corn for ethanol

a. Almost any plant-based material can made into ethanol. All plants contain sugars, and those sugars can be fermented to make ethanol. Plant material also can be converted to ethanol using heat and chemicals.

b. Today, nearly all ethanol produced in the world is derived from starch- and sugar-based feedstocks. Corn serves as the feedstock for most U.S. ethanol production.[201] Its C4 carbon fixation process (also found in sugarcane) is relatively uncommon among plants and unusually efficient – producing four-carbon compounds instead of the usual three.[202]

i. Only about 3% of flowering plant species use the C4 pathway, but this relative handful accounts for 23% of all terrestrial carbon fixation.[203]

c. Cellulose (plant fiber) also offers several advantages as a biofuel feedstock: It is abundant and can be derived from either agricultural waste or non-food crops such as switchgrass and miscanthus. However, it is challenging to access the sugars in these feedstocks for conversion,[204] and cellulosic ethanol remains more expensive than corn ethanol, which traded for $1.60 a gallon or less for most of the last five years – albeit with a recent spike in 2021.[205] That is roughly half the cost of cellulosic ethanol, which is burdened by the high capital costs of pioneer facilities.[206]
d. The effect of increased corn production to meet ethanol demand has been a subject of long-standing contention in U.S. agricultural and environmental policy.
    i. The amount of land planted in corn rose from 60 million acres in 1983 to roughly 90 million since 2010, much of that due to expanding ethanol production, which now accounts for nearly 40% of total corn use.[207] Yet that represents a shift in cropland more than an increase: The overall amount of U.S. cropland in production has changed little over the last 30 years, varying between 300 and 330 million acres+.[208] [209]
    ii. Corn yields have increased at a remarkably steady rate of about 1.9 bushels per acre per year since the mid-1950s – quadrupling in that time from 40 to 170 bushels per acre.[210] Between 2002 and 2017 U.S. agriculture gained about 669 million metric tons of corn due to yield improvement. That is equivalent to about 71 billion gallons of ethanol (45% of the ethanol produced during that period) plus 223 million metric tons of byproducts for animal feed.[211]
    iii. Modern farming uses low-impact, "precision" techniques that require less land, less energy and fewer chemicals for every bushel produced. Since 1980, irrigation water use per bushel has fallen by 46%, energy use by 41%, and greenhouse-gas emissions by 31%.[212]
    iv. With increased acreage and yields meeting the demand for ethanol, the price of corn (apart from a sudden spike in the first half of 2021) traded in a narrow range for the past six years, about half its peak in 2012[213] and lower than the average inflation-adjusted price from 1981 to the present.[214] [215]
    v. Concerns about the impact of ethanol production on food prices have largely abated over that time. A study of eight Asian economies found that 64% of the variance in food prices was explained by oil price movement, and only 2% by biofuel prices.[216]
    vi. Controversial claims about large negative "indirect land use" effects of increased corn production have not been borne out by data, as shown in a recent review of the research.[217] Life-cycle analyses by ICF and Argonne both reflect modest assessments of indirect land use effects.[218] [219] EPA and California regulators include land-use factors in their evaluations of ethanol's GHG emissions,[220] and California's figure, for example, is only 19% of the very high estimate that kicked off the debate.[221] Argonne's recent retrospective analysis found that the initial estimate was at least five times overstated – indeed, by Argonne's estimate, nearly 15 times.[222]
    vii. The Energy Information Administration projects that demand for gasoline will decline from 137.5 billion gallons per year in 2021 to 127 billion gallons in 2050,

due to increased vehicle efficiency and greater use of electric vehicles.[223] Fueling the 2050 fleet with higher-level blends such as E30 thus would require little more than a doubling of today's ethanol capacity. Demand will fall further if electric vehicles are adopted more rapidly than currently envisioned.

- **Note:** The recurrent affliction of American farmers is overproduction and low prices. Increased demand for ethanol in higher-level blends could be met within today's cropland +footprint, absorbing that overproduction and helping to restore farm income. A more robust future market for ethanol would also attract additional investment to the production of next-generation biofuels from cellulosic feedstocks – investment that has been lacking in the face of a saturated market for E10.

e. Environmental concerns about the effects of increased agricultural production on water quality (due to nitrogen fertilizer runoff) can be addressed directly with incentives for improved conservation practices that would increase the amount of carbon sequestered in the soil.
    i. Corn may be a particular beneficiary of carbon sequestration incentives, according to studies that looked at carbon stored below the 30-centimeter depth usually measured (12 inches). A long-term study by USDA in eastern Nebraska found that corn grown with best management practices had average annual increases in soil organic carbon of one ton per acre, more than half of it below the 30 cm depth.[224]

- **Note:** A combination of best practices – the use of renewable natural gas in processing and carbon-sequestering techniques on the farm – would bring corn ethanol's carbon footprint almost to zero, and carbon capture and storage after processing would make it a carbon-negative fuel.

4. EPA regulation of ethanol blends

a. The Clean Air Act prohibits fuel manufacturers from introducing into commerce, or increasing the concentration of, new fuels and fuel additives unless they are "substantially similar" to fuels or fuel additives used in the certification of motor vehicles.[225]
    i. Since EPA now uses E10 as its certification fuel for new vehicles, increasing the concentration of ethanol in gasoline is not prohibited.

b. The law separately limits Reid vapor pressure (RVP) – a measure of the fuel's propensity to give off evaporative emissions – for fuel blends containing gasoline and 10% ethanol (E10).[226] EPA granted RVP waivers in 2010 and 2011 to enable the use of E15 in late-model vehicles – those produced from model year 2001 on.

c. In 2019 EPA issued an interpretive rulemaking defining gasoline blended with up to 15% ethanol as "substantially similar" to the E10 fuel it has used since 2014 to certify all new motor vehicles.[227] Referring to the RVP limit, EPA said, "We are interpreting this language as establishing a lower limit, or floor, on the minimum ethanol content … rather than an upper limit on the ethanol content."[228] However, a federal appeals court struck down that action in 2021.[229]

i. EPA said in its rulemaking, "We are confident that relative evaporative emissions effects for E15 would largely be similar or slightly less than those for E10."[230] Since the RVP of ethanol blends reaches its maximum level at E10 and then declines as more ethanol is added, this conclusion would be equally true of higher-level blends.[231] [232] In fact, the RVP of E30 is similar to that of E0.[233]

- **Note:** EPA could either certify E30 fuel based on an application from an automaker or simply define E30 as "substantially similar" to E10. The benefits derived from adding ethanol to gasoline – in terms of reduced emissions and improved performance that offsets the lower energy content of ethanol – appear to be optimized around the 30% blend level – as Thomas Midgley found a century ago.

d. Citing the need for "the development of infrastructure and promotion of fuels, including biofuels, which will enable the development and widespread deployment of advanced technologies," in May 2010 President Obama issued an Executive Memorandum requesting that EPA "review for adequacy the current non-greenhouse gas emissions regulations for new motor vehicles, new motor vehicle engines, and motor vehicle fuels, including tailpipe emissions standards for nitrogen oxides and air toxics, and sulfur standards for gasoline." Yet no action addressing fuels or mobile source air toxics resulted.[234]
e. Regarding other air pollutants, a 2008 study by the National Renewable Energy Laboratory found that increasing ethanol content (to E20) reduced hydrocarbon emissions while increasing emissions of ethanol and aldehydes. Vehicles that used a power enrichment strategy called long-term fuel trim (LTFT) to adjust the engine's air-fuel ratio showed no statistically significant fuel effect on emissions, including NO_x.[235]
    i. Automakers can readily adjust the engine's air-fuel ratio to keep NO_x emissions within permissible levels: A 2014 Ford study of a flexible fuel vehicle found that NO_x emissions decreased by approximately 50% as the ethanol content increased from zero to E30-E40. The study pointed to the importance of engine calibration: "Upon sensing greater ethanol content in the fuel, the calibration prescribed different engine operating conditions."[236]
    ii. Aldehyde emissions can be controlled with a conventional oxidation catalyst.[237]

IV. The urgency of action

Dr. Frederica P. Perera is Professor of Environmental Health Sciences and Founding Director of the Columbia Center for Children's Environmental Health, currently serving as Director of Translational Research. She is internationally recognized for pioneering the field of molecular epidemiology, utilizing biomarkers to understand links between environmental exposures and disease. Her research, cited above, addresses the multiple impacts of fossil fuel combustion on children's health and development – both from the toxic pollutants emitted, such as PAHs, and from climate change related to CO_2 emissions.[238] The following commentary, while not addressing aromatics specifically, is nonetheless eloquently on point. It is drawn from her paper "Multiple Threats to Child Health from Fossil Fuel Combustion: Impacts of Air Pollution and Climate Change":

> Fossil-fuel combustion by-products are the world's most significant threat to children's health and future and are major contributors to global inequality and environmental injustice. The emissions include a myriad of toxic air pollutants and carbon dioxide (CO_2), which is the most important human-produced climate-altering greenhouse gas. Synergies between air pollution and climate change can magnify the harm to children. Impacts include impairment of cognitive and behavioral development, respiratory illness, and other chronic diseases – all of which may be "seeded" in utero and affect health and functioning immediately and over the life course.
>
> By impairing children's health, ability to learn, and potential to contribute to society, pollution and climate change cause children to become less resilient and the communities they live in to become less equitable. The developing fetus and young child are disproportionately affected by these exposures because of their immature defense mechanisms and rapid development, especially those in low- and middle-income countries where poverty and lack of resources compound the effects. No country is spared, however: Even high-income countries, especially low-income communities and communities of color within them, are experiencing impacts of fossil fuel-related pollution, climate change and resultant widening inequality and environmental injustice. Global pediatric health is at a tipping point, with catastrophic consequences in the absence of bold action.
>
> Fortunately, technologies and interventions are at hand to reduce and prevent pollution and climate change, with large economic benefits documented or predicted. All cultures and communities share a concern for the health and well-being of present and future children: This shared value provides a politically powerful lever for action.[239]

V. Summary and recommendations

The use of aromatics in gasoline is an unnecessary cause of toxic air pollution that harms and shortens lives – as a major contributor to fine particle emissions, especially dangerous PAHs and secondary organic aerosol. These emissions are a menace to the health and cognitive development of millions of children who live in high-traffic areas. EPA has yet to fulfill its statutory obligation to produce the greatest degree of emission reduction achievable in the hazardous air pollutants from motor vehicles and motor vehicle fuels.[240] The risk to public health has been increased by the shift to new automotive direct-injection engine technology.

Pollution causes many threats to public health, not all of which can be cost-effectively regulated, but it is hard to imagine one that could be solved more easily or at less cost than this one. Reducing the use of aromatics requires only a minor regulatory adjustment and would deliver important benefits for both public health and the environment. Reconsideration of national fuel economy standards will provide an opportunity for EPA to:

- Immediately permit the sale and use of higher-level ethanol blends.
- Encourage their adoption as a standard fuel for vehicles sold in model year 2025 and beyond.
- Reduce the cap on aromatic content in gasoline by half – to no more than 12.5% in reformulated gasoline, much as it imposed a cap on benzene in 2007.[241]

The California Air Resources Board should do likewise, and its Low Carbon Fuel Standard should become a model for federal legislation, replacing the Renewable Fuel Standard at the national level. Concurrently, automakers should be encouraged to optimize their vehicle designs to take best advantage of ethanol's beneficial attributes.

We are on the cusp of a rapid global shift to electric vehicles as a necessary and urgent response to climate change, but internal combustion engines will remain a substantial part of the light-duty fleet until mid-century. As a transition strategy for the next 30 years, reducing aromatics through the increased use of ethanol would have significant near-term climate benefits for the transportation sector. The public health benefits – especially to newborn children – demand this change and could be replicated at greater scale, to even greater effect, worldwide.

High-priority opportunities for immediate action

The Clean Air Act prohibits fuel manufacturers from introducing into commerce, or increasing the concentration of, new fuels and fuel additives unless they are "substantially similar" to fuels or fuel additives used in the certification of motor vehicles. Since EPA now uses E10 as its certification fuel for new vehicles, increasing the concentration of ethanol in gasoline to E30 would be permissible.

- EPA should define gasoline blended with 30% ethanol as "substantially similar" to E10. The benefits derived from adding ethanol to gasoline – in terms of reduced emissions and improved performance that offsets the lower energy content of ethanol – appear to be optimized around the 30% blend level.

- Concurrently, upon an automaker's request for approval of an E30 certification fuel, EPA should move quickly to grant it. This would, among other things, resolve any remaining uncertainties about the effect of higher levels of ethanol on pollutants such as nitrogen oxides and aldehydes,

which can be managed by appropriate engine settings and emissions technology. Approval would be a green light to automakers to optimize their new vehicles for higher-octane fuel – enabling them to improve vehicle efficiency and performance.

Near-term regulatory opportunities

- EPA should incorporate the use of higher-octane fuels as an available control strategy for reducing greenhouse gas emissions under its forthcoming revision of the Safer Affordable Fuel-Efficient (SAFE) Vehicles Rule. It should set a minimum octane standard for gasoline used in light-duty vehicles, and that standard should ensure the use of biofuels, not aromatics, to increase octane – either by setting the standard high enough to preclude the use of aromatics only, or by capping the permissible level of aromatics in fuel (at 12.5%, half the current limit for reformulated gasoline), or both.

- EPA and NHTSA should review and revise available incentives for alternative fuels to support the use of biofuels. In particular, the agencies should discard their outdated analysis of ethanol's life-cycle greenhouse gas footprint and conform it to the most recent assessments from USDA and Argonne National Laboratory.

- EPA should revise its MOVES model, which estimates emissions for mobile sources at the national, county, and project level for criteria air pollutants, greenhouse gases, and air toxics. A 2014 update based on erroneous modeling assumptions led the model to predict incorrectly elevated emissions factors for ethanol blends.

- More generally, EPA should undertake a thorough revision of its air quality models, which fail to account for secondary organic aerosol – a major contributor to deadly fine particle pollution – and should rely more heavily on atmospheric measurement of pollution levels instead of model predictions.

Longer-term legislative opportunities

The Renewable Fuel Standard has served its purpose but is not well adapted to the urgent need to reduce greenhouse gas emissions. California's Low Carbon Fuel Standard (LCFS) has demonstrated the value, impact, and effectiveness of market-based price incentives for performance and should be adopted by Congress as a substitute for the RFS.

- Congress should develop a national LCFS reflecting "the best-available science about the carbon intensity of fuel production, farming practices, land use changes, and crop productivity." Such a standard should reward producers that use "climate-smart practices that reduce carbon emissions, store soil carbon, and reduce nitrous oxide emissions." In particular, credit for soil carbon sequestration under a national LCFS would incentivize farmers to employ improved conservation practices that would minimize the environmental impacts of corn production.

- Congress should provide incentives to retail gasoline outlets to encourage them to update their refueling infrastructure, including UL-certified pumps and waterproof underground tanks.

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