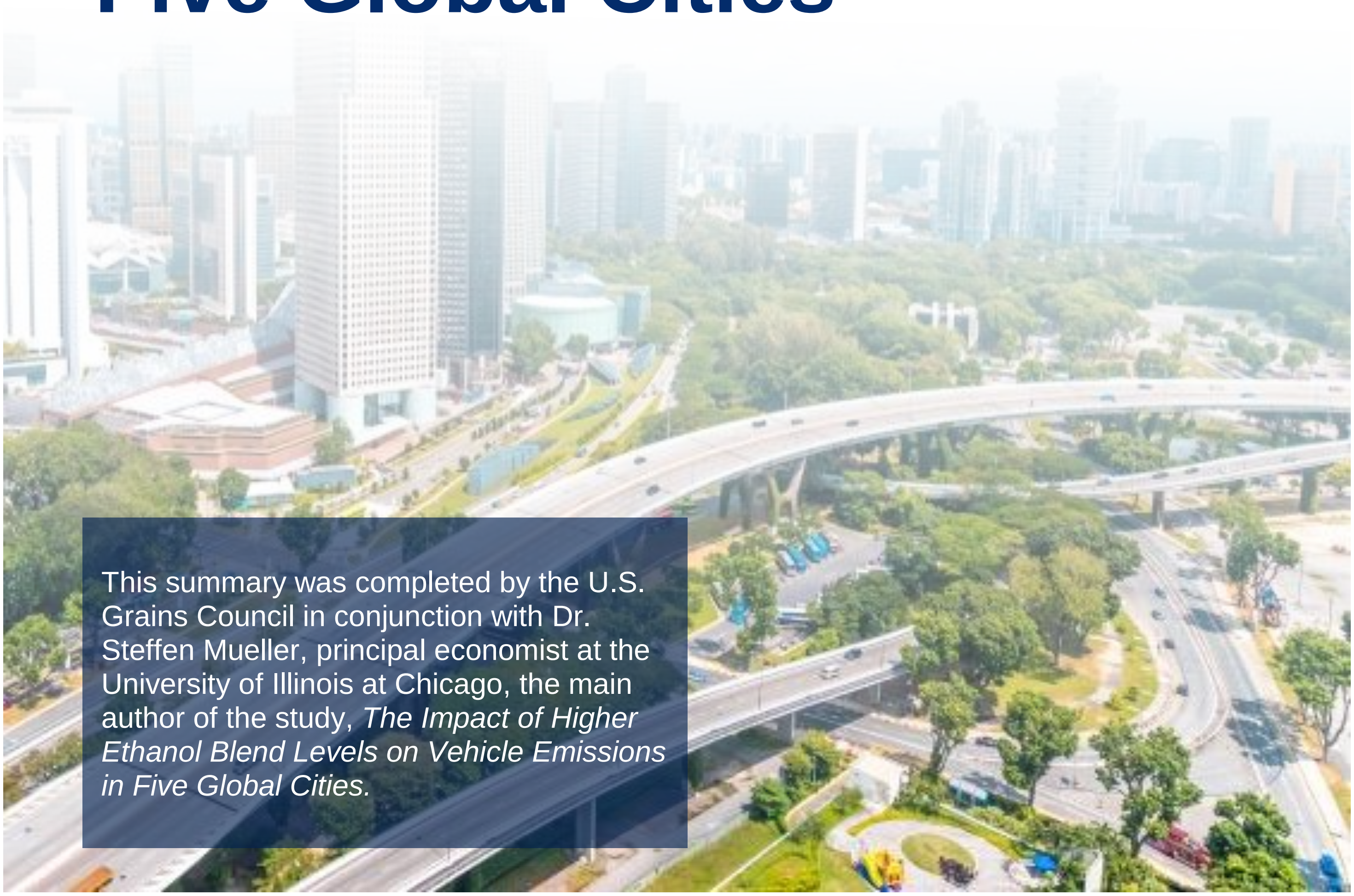
Higher Ethanol Blend Levels Reduce Vehicle Emissions in Five Global Cities



This summary was completed by the U.S. Grains Council in conjunction with Dr. Steffen Mueller, principal economist at the University of Illinois at Chicago, the main author of the study, *The Impact of Higher Ethanol Blend Levels on Vehicle Emissions in Five Global Cities.*

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EXECUTIVE SUMMARY

1.1 Ethanol Improves Our Health and Environment Today and Tomorrow

Clean air is vital for both human health and the health of the planet. Passenger vehicle emissions cause increased respiratory ailments, heightened risk of life-threatening conditions, and other health care system burdens, while contributing to carbon emissions, ocean acidification, ozone depletion, and changes in plant growth and soil nutrient levels. However, there are ways to reduce the effects of emissions by blending ethanol.

A recent University of Illinois at Chicago study – *The Impact of Higher Ethanol Blend Levels on Vehicle Emissions in Five Global Cities* – determined that adopting higher ethanol blends would reduce vehicle emission toxins, improve human health outcomes, lower greenhouse gas (GHG) emissions, and provide increased profits for refiners. Any actions to reduce the impacts of pollution will improve the quality of life for us today and for future generations. Incorporating ethanol into gasoline delivers health, environmental, and economic benefits.

FIVE CITIES STUDIED

1.2 Cleaner Air to Breathe for Better Health

Blending ethanol into gasoline would reduce total hydrocarbon (THC) emissions and volatile organic compound (VOC) emissions in all cities studied. Adoption of E10 and E20 blends would also reduce the risk of hazardous ozone formation. Reducing these negative impacts would help avoid damage to the immune, respiratory, and nervous systems, particularly for babies in utero, children, older adults, and those with chronic respiratory or cardiovascular health conditions. Ethanol blends can also reduce the damaging compounds that irritate our skin and eyes and cause visible smog in cities.

Furthermore, the study results showed that higher ethanol use would significantly reduce toxic emissions that endanger human health, such as polycyclic

E10 and E20

Ethanol blends contain 10 or 20 percent mixture of anhydrous ethanol, while the other 90 or 80 percent is crude-based gasoline.

compounds linked to cancer, carbon monoxide (CO) linked to heart disease, and total weighted toxins linked to a myriad of negative health effects. The study utilized a weighted toxins measure to accurately reflect not only the quantity of toxins but the damage each inflicts on human health.

In all five cities, substituting E10 blends for current gasoline would result in an average 15.2 percent decrease in weighted toxins, while E20 blends would reduce toxins even more significantly (31.7 percent on average).

Overall, the decrease in emissions from blending ethanol is estimated to yield a net reduction of approximately 200-300 lifetime cancer cases per city that are directly associated with key pollutants in vehicle exhaust. Avoiding these cancers will save several thousand years of life lost in each city, tens of millions of dollars of direct healthcare costs for cancer treatment, and adverse impacts to quality of life, loss of income, and devastation to families.

1.3 Healthier Environment through Few Emissions

With its lower greenhouse gas (GHG) emissions, ethanol also reduces the environmental damages associated with gasoline. GHG emissions can lead to ocean acidification, changes in plant growth and nutrition levels, ozone layer depletion, and changes in climate, as well as increased smog and ozone pollution. The study calculated life-cycle emissions for ethanol produced and shipped from the U.S. to each of the five cities and then blended on location. Compared to emissions from gasoline currently produced in the countries, GHG emissions from blended gasoline were on average 3.7 percent and 7.4 percent lower for E10 and E20, respectively.

1.4 Stronger Economy with Refining Profits

Blending ethanol not only leads to cleaner air to breathe and less damage to the environment, it can help refiners enjoy increased revenues. Traditional gasoline requires complex refining of crude components to create the necessary properties for gasoline. Ethanol adds some of these needed properties, so crude components do not need to be as heavily processed. The decreased processing of the crude results in greater total gasoline volume produced from the same amount of inputs and therefore more saleable product.

Hydrogen is another consideration in ethanol blending impacts. When crude inputs are processed, hydrogen – a key byproduct from a processing unit called the catalytic reformer – is produced and reused elsewhere in the refinery. With ethanol blending, less processing occurs, and therefore hydrogen production decreases and may need to be replaced from another source.

After accounting for these two key changes in the refining process across the five cities, refiners would break even or benefit from increased revenue (up to $12 per barrel of gasoline) from E10 blended fuel. For E20 blends, refiners' profits would rise between $10 to $27 per barrel, depending on the city.

STUDY OVERVIEW AND KEY RESULTS

2. Introduction

The Impact of Higher Ethanol Blend Levels on Vehicle Emissions in Five Global Cities by Mueller et. al. examined the cumulative reduction in tailpipe and GHG emissions from adopting higher ethanol blends for the light-duty vehicle market – passenger cars and light trucks. The study identified the emission savings based on current and predicted fuel demand and also assessed refinery profitability considerations associated with producing these fuels. The focus cities – Beijing, Mexico City, New Delhi, Seoul, and Tokyo – were selected because they each face major air quality challenges.

To facilitate the exploration of likely scenarios, the authors developed a spreadsheet-based model termed the International Biofuels Emissions Analysis Model (iBEAM). The study's scenarios compared emissions differences between current gasoline use without ethanol and ethanol-blended gasoline. Unlike the U.S. Environmental Protection Agency's (EPA) MOtor Vehicle Emission Simulator (MOVES), the developed model allows users to incorporate data from the latest ethanol-gasoline blend vehicle emissions studies, while still accounting for key emissions aspects such as vehicle retirement and emissions control deterioration over time. The model allows for transparency and easy model adjustment for emissions calculations.

Utilizing the iBEAM model analysis, the authors relied upon a box model to convert emissions (tonnes) into atmospheric concentrations. This allowed health risk factors to be applied and subsequently allowed the authors to quantify the impact on cancer cases, health cost, and years of life lost when examining health impacts.

For GHG emissions calculations, the study relied on two proven data sources for its iBEAM model. First, the study used data from the Greenhouse gases, Regulated Emissions and Energy use in Transportation (GREET) model developed by Argonne National Laboratory. This model is the gold standard for U.S.-based life-cycle analysis and contains the most up-to-date information on corn ethanol production. Second, the authors used the BioGrace model, which is a European life-cycle model that evaluates European fuel pathways under the Renewable Energy Directive (RED).

Finally, by identifying the impact on refining profits, the authors determined how the supply chain would react to adopting higher ethanol blends. To complete this assessment, net revenues were calculated from the incremental changes in hydrogen and gasoline output relative to the base-case gasoline in each city. Estimated changes to these two key outputs rely on the derived gasoline recipes of gasoline samples taken in each city. By comparing the refinery outputs for gasolines blended with and without ethanol, the study's authors estimated changes in revenue on a per barrel of gasoline basis.

The results highlight for decision makers why ethanol should be considered as part of the solution. The authors rigorously incorporated the most recent research on gasoline and ethanol production and usage to design a systematic approach for quantifying the benefits of blending.

The rest of this summary serves as a high-level overview of the methodology behind the findings. The full technical academic paper can be found at http://www.erc.uic.edu/biofuels-bioenergy/.

3. Key Study Results

3.1 Reduced Emissions from Blending Creates Cleaner Air to Breathe for Better Health

The study demonstrates why including ethanol as a public health strategy makes sense:

- *It shows substantial decreases in several carcinogenic, ozone-forming, and health-hazardous compounds*
- *Incorporating ethanol blends into the projected gasoline vehicle fleet would save more carbon monoxide (CO) and weighted toxin emissions than saved from the projected electric vehicle (EV) adoption rate*
- *Lowering emissions reduces respiratory and cardiovascular associated health costs due to breathing cleaner air*
- *Reducing cancer cases avoids several thousand years of potential life lost, direct healthcare costs for cancer treatment, adverse impacts to quality of life, loss of income, and devastation to families in each city*

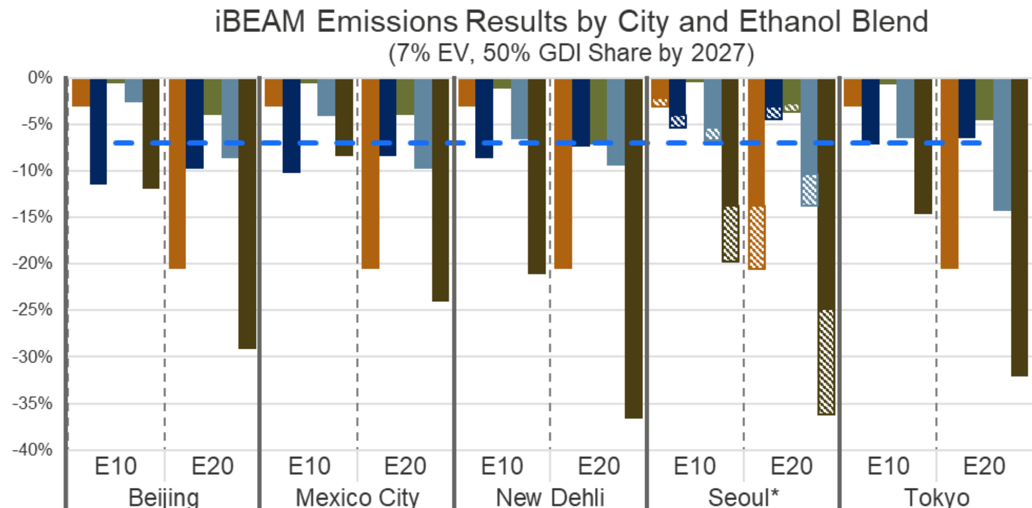
Relying upon rigorous methodology and past work, the authors estimated the emissions changes in tonnes and percent by city and by ethanol blend as a key output of their iBEAM model. As shown in the table and chart below, on a total tonnage and percentage basis through the year 2027, the results showed reduction in hydrocarbon – total hydrocarbons (THC) and volatile organic compounds (VOC) – across all cities from E10 and E20 blends, which should result in reduced risk for ozone formation.

Furthermore, the study found significant reductions in CO emissions (linked to heart disease and other negative health effects), total hydrocarbons, particulate matter (PM), and weighted air toxins (also correlated with cancer). For air toxins, the four main toxins (benzene, acetaldehyde, formaldehyde, 1,3-butadiene) were multiplied by their respective cancer potency factors to derive the total weighted toxins measure. The study also showed that nitrogen oxide (NOx) emissions remain unaffected or slightly decreased by ethanol blends, as shown in *Table 1*.

Table 1: Summary of Emission Reductions in Tonnes by City and Ethanol Blend (2016-2027)

	Beijing		Mexico City		New Delhi		Seoul		Tokyo	
	E10	E20	E10	E20	E10	E20	E10	E20	E10	E20
CO	-69,613	-462,832	-94,806	-630,332	-21,844	-145,236	-15,004	-99,754	-21,480	-142,811
THC	-29,238	-24,866	-25,953	-21,593	-9,842	-8,353	-3,562	-2,968	-5,137	-4,581
PM	-10	-58	-11	-69	-6	-35	-1	-8	-4	-23
NOx	*Unchanged or slightly decreased*									

Figure 1 shows that blending E10 reduces these weighted toxins an average of **15%** across the five cities examined. Blending E20 leads to even greater health benefits by cutting weighted toxins an average of **32%**, polycyclics by **11%**, and CO emissions by **21%**. Additional detail on how weighted toxins were calculated is highlighted in section *5.4.1 Total Weighted Air Toxins and Cancer Risk Assessment*.



	Beijing E10	Beijing E20	Mexico City E10	Mexico City E20	New Dehli E10	New Dehli E20	Seoul* E10	Seoul* E20	Tokyo E10	Tokyo E20
CO	-3.1%	-20.6%	-3.1%	-20.6%	-3.1%	-20.6%	-3.1%	-20.6%	-3.1%	-20.6%
THC	-11.5%	-9.8%	-10.2%	-8.5%	-8.7%	-7.4%	-5.5%	-4.6%	-7.2%	-6.5%
PM	-0.7%	-4.0%	-0.7%	-4.0%	-1.2%	-7.1%	-0.6%	-3.4%	-0.8%	-4.6%
Polycyclics	-2.7%	-8.6%	-4.1%	-9.8%	-6.6%	-9.4%	-7.0%	-13.7%	-6.5%	-14.4%
Weighted Toxins	-12.0%	-29.2%	-8.4%	-24.0%	-21.2%	-36.6%	-19.8%	-36.3%	-14.7%	-32.1%
EV Savings	-7.0%	-7.0%	-7.0%	-7.0%	-7.0%	-7.0%	-7.0%	-7.0%	-7.0%	-7.0%

Figure 1: Summary of Emissions in Percent by City and Ethanol Blend

The emissions results are relevant in light of the recent policy and public discourse on EV deployment. A comparison between ethanol and EVs (dashed blue line in *Figure 1*) shows that EVs through 2027 would save approximately the same amount of THC/VOC emissions as a fleet change to E10 and E20 and that EVs would provide significantly less savings for CO and weighted toxins. Since ethanol can be used in existing vehicles, emissions savings can be realized immediately, unlike EVs, where those savings depend on the adoption of this technology in the future. Note that these are tailpipe emissions only and do not include any upstream emissions from electricity production for EVs, which, in many of the studied countries, may come from coal-fired power plants, decreasing the overall benefits of EVs.

The academic paper identifies all model inputs for each city, including the projected number of gasoline vehicles with the corresponding EV and gasoline direct injection (GDI) engine share, the projected fuel use and fuel economy, and the vehicle distance traveled to generate the reported results. Model outputs include a full list of the key pollutants emitted in tonnes by year (and totals over the studied time period).

Utilizing the modeled results of the vehicle emissions reductions due to adding ethanol to gasoline, the authors converted these reductions into atmospheric concentrations.

The change in concentration, and hence the benefit, is derived from the substitution of high-octane value ethanol for aromatics such as benzene and polycyclics, some of which are toxic. By calculating concentration, health risk factors could be applied in order to subsequently quantify the impact on cancer cases, years of life lost, and health cost.

Table 2: Summary of Change in Cancer Cases by Pollutant by City and Ethanol Blend

	Acetaldehyde	Benzene	Polycyclics	1,3-Butadiene	Formaldehyde
E10					
Beijing	5.2	-79.0	-30.6	-97.9	-3.3
Delhi	3.9	-95.7	-59.8	-107.8	-2.2
Mexico City	10.5	-123.2	-43.5	-142.8	-9.5
Seoul	2.9	-33.9	-40.3	-83.5	-1.4
Tokyo	2.7	-39.4	-42.5	-76.5	-1.5
E20					
Beijing	13.7	-116.3	-99.6	-287.4	-4.6
Delhi	10.7	-136.9	-85.4	-251.7	-2.8
Mexico City	27.5	-192.6	-95.7	-456.7	-12.5
Seoul	7.3	-44.4	-79.2	-207.7	-2.4
Tokyo	7.3	-57.6	-93.4	-288.9	-2.1

The authors estimated the change in number of lifetime cancer cases resulting from the introduction of ethanol fuels, which is depicted for each selected toxin in *Table 2*. It should be noted that the emissions for the "possibly known carcinogen in humans," acetaldehyde (US EPA, n.d.), is estimated to increase with the use of ethanol fuels, resulting in an increase in the estimated number of associated cancers. However, the increase in cases from acetaldehyde is small relative to the reduction in cases related to benzene, butadiene, benzopyrene/polycyclics, and formaldehyde, all of which are known carcinogens to humans (US EPA 2017; IARC 2012; Baan et al. 2009). Estimated expected years of life lost or saved associated with the change in the number of cancer cases varied depending upon city.

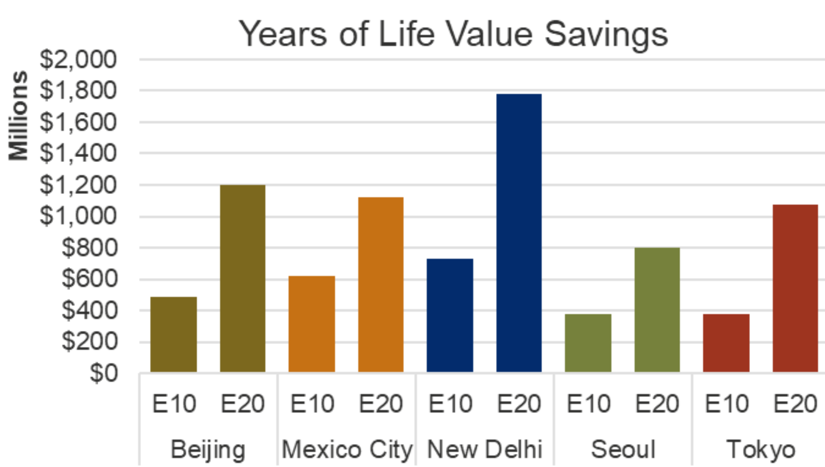


Figure 3: Summary of Years of Life Value Savings by City and Ethanol Blend

The introduction of E10 saves between ~2,500 and ~4,900 years of potential life, with more significant savings from E20 of ~5,400 to ~11,800 years due to the reduction in lifetime cancer cases. In the U.S., a person-year of life lost has been valued at $150,000, undergirding the study's assessment, recapped in *Figure 2,* that ethanol blending would result in several hundred million dollars of savings (Yabroff et al. 2008) across the five cities.

Ethanol fuels are not only predicted to save years of life but also to save millions of dollars within the healthcare system for direct cancer treatment costs related to continued use of current gasoline.

Blending ethanol is estimated to yield a net reduction of approximately 200-300 cancers cases per city. Avoiding these cancers will avoid the costs previous highlighted, as well as the adverse impacts to quality of life, loss of income, and devastation to families.

3.2 Ethanol's Lower GHG Emissions Decreases Environmental Damages

The study demonstrates clear environmental benefits of blending ethanol through reductions in GHG emissions:

- *Lower GHG emissions help preserve the globe's sensitive ecosystems*
- *Regardless of the common emissions model used, all show quantifiable and significant environmental benefits*

In addition to assessing health benefits from blending ethanol, the study also assessed the GHG emissions on a life-cycle basis for ethanol produced and shipped from the U.S. to each of the five studied cities and blended on location into E10 and E20 gasolines. To identify impacts, the emissions from blended gasoline were then compared to current gasolines produced in the five countries.

The study employed three life-cycle analysis methods for evaluation – GREET substitution, GREET allocation, and BioGrace European Joint Research Center method. The GREET substitution method incorporated a substitution credit for the animal feed coproduced at the ethanol plant. The GREET allocation and BioGrace methods incorporated an allocation of energy based on the energy emissions from all products produced at the ethanol plant. The iBEAM model displayed these energy inputs and emissions from corn ethanol over the life cycle, from farming to end use.

The GHG savings were similar regardless of the modeling choice. The total cumulative GHG savings are represented in *Figure 3*, based on the GREET allocation method.

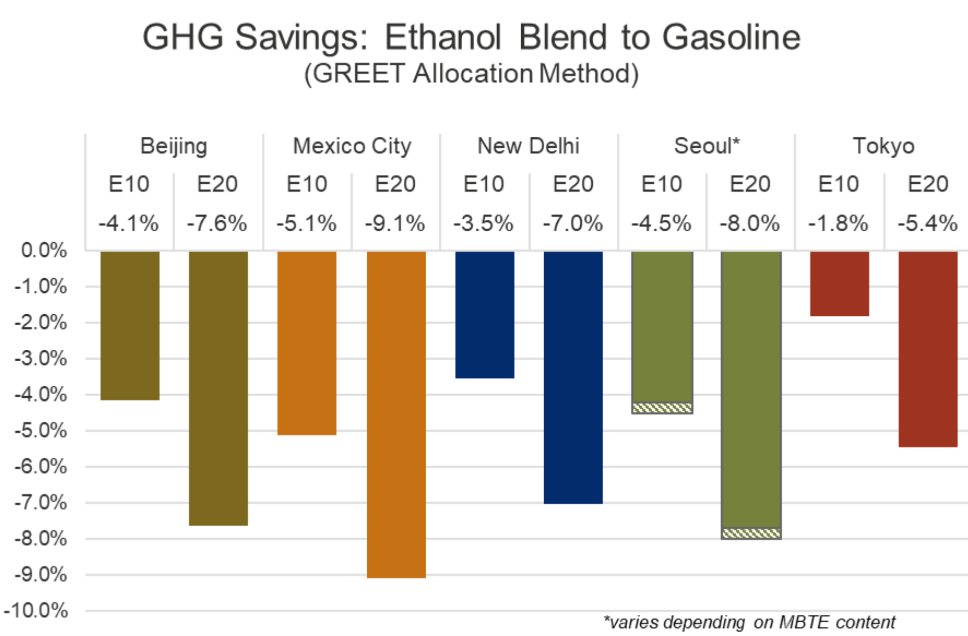


Figure 3: Cumulative GHG Savings by City and Blend

Cities with high fuel demand that currently use methyl tert-butyl ether (MTBE) in gasoline recipes can realize large GHG savings due to the high levels of GHG produced in MTBE production.

3.3 Blending Ethanol Increases Refining Profits

Not only is ethanol blending good for human health and the environment, there are also potential economic benefits associated with blending, including:

- *Increasing gasoline volumes through blending boosts the total saleable product, and therefore revenues, for refiners*
- *Adding ethanol creates equal or greater profit than gasoline at the E10 level, and always generates more profit when blending E20*

Gasoline volume changes with blending are the ultimate source of blending profits. When blending ethanol – an oxygenate that adds needed octane to gasoline – major crude components do not need to be as heavily refined. While this results in increased total gasoline volume, less processing reduces the production of hydrogen from a refining unit called the catalytic reformer. Since less hydrogen is captured, a key byproduct reused elsewhere in the refinery, it may have to be replaced with other sources. The study examined these incremental changes in hydrogen and gasoline production to determine impacts on refining profits for gasoline produced in each of the five cities. Per barrel profits varied due to current base gasoline used in each city and refining capacities.

Using average prices for gasoline and natural gas, blending E10 would result in comparable or higher refiner revenues, ranging from $1 to $12 per barrel. Due to projected increases in total gasoline volumes, even greater revenue gains could be realized by refiners from blending E20, ranging from $6 to $27 per barrel, as illustrated in *Figure 4*.

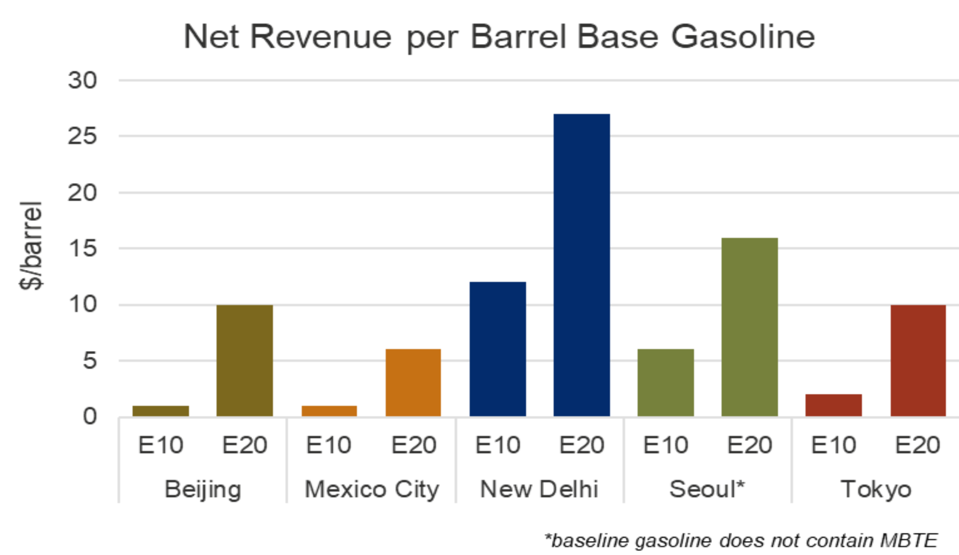


Figure 4: New Revenue Adjustments to Refiners from Adopting Ethanol Blends

METHODOLOGY AND BACKGROUND

4. Quantifying the Benefits of Ethanol Blending

This section outlines how the study *The Impact of Higher Ethanol Blend Levels on Vehicle Emissions in Five Global Cities* by Mueller et al. arrived at its conclusions. This section aims to assist the reader in understanding the study methodology. The original study can be referenced at http://www.erc.uic.edu/biofuels-bioenergy/ for those seeking a comprehensive technical approach.

4.1 Structure of the iBEAM Emissions Model

The study's authors developed a spreadsheet-based model termed the International Biofuels Emissions Analysis Model (iBEAM) for tailpipe emissions assessments. It was designed to draw on existing information, research, and previous models and incorporate them in a transparent way.

To consider vehicle emissions, the model estimated the current and future vehicle set on the road. By characterizing a set of vehicles, an emission factor assessment for both gasoline and ethanol was conducted to determine total emissions adjustments from ethanol-blended gasoline. The vehicle characterization included a projection of annual gasoline passenger cars on the road multiplied by the distance traveled annually by each car to calculate the total driven passenger distance (total kilometers) in each city. The passenger car population was corrected for projected EV share and broken out by annual new car additions, including replacement of retired vehicles.

To best reflect reality, a few model corrections were introduced. Among them was a correction of emissions factors by vehicle age. Additionally, the effects of altitude and Reid vapor pressure (RVP) – the point at which a liquid becomes a gas due to its evaporation characteristics – was added for hydrocarbon (HC) emissions. Additionally, the model accounted for an explicit representation of refueling losses, permeation, spillage, and onboard refueling vapor recovery (ORVR) technologies.

The emissions factors for both gasoline and ethanol were assessed in two different ways – through sampling/modeling and by using existing emission standards and research:

- First, the study used the U.S. EPA Complex Model to derive emissions factors for gasoline and blended gasoline. To get the appropriate parameters, multiple country-specific gasoline samples were collected and analyzed. Researchers derived emissions factors for the base gasoline – gasoline currently being used – and then by adjusting the model for ethanol blending, generated another set of emission factors to compare to the base gasoline estimates.

- Second, to verify the first method and use the best available information, the authors relied on additional emissions factors for gasoline from past, current, and future emissions standards governing each city studied. For vehicle emissions, the authors surveyed prior major studies and summarized the expected impact from ethanol on combustion emissions to create emission factors for ethanol.

After emissions, the authors additionally identified GHG savings from blending by relying on the vehicle characterization and total fuel utilized in each of the five cities. They calculated a carbon dioxide equivalent (a standard measure for GHG emissions) by relying on two well-known models – GREET and BioGrace. The two life-cycle models incorporated data from iBEAM about projected vehicles and quantified any changes or savings from ethanol.

Beyond tailpipe and GHG emissions, the study also assessed refiner profitability for adding ethanol to current gasoline recipes. The model first assessed the additional gasoline volume refiners would be able to generate by blending ethanol to the current base gasoline, resulting in more saleable product and revenue. That additional revenue was compared against the cost of supplementing hydrogen to offset the lower amount of hydrogen produced within a refinery's catalytic reformer unit.

The study predicted the impact on refinery revenues from production of E10 and E20 fuels alongside its emissions assessments. *Figure 5* represents the model's structure.

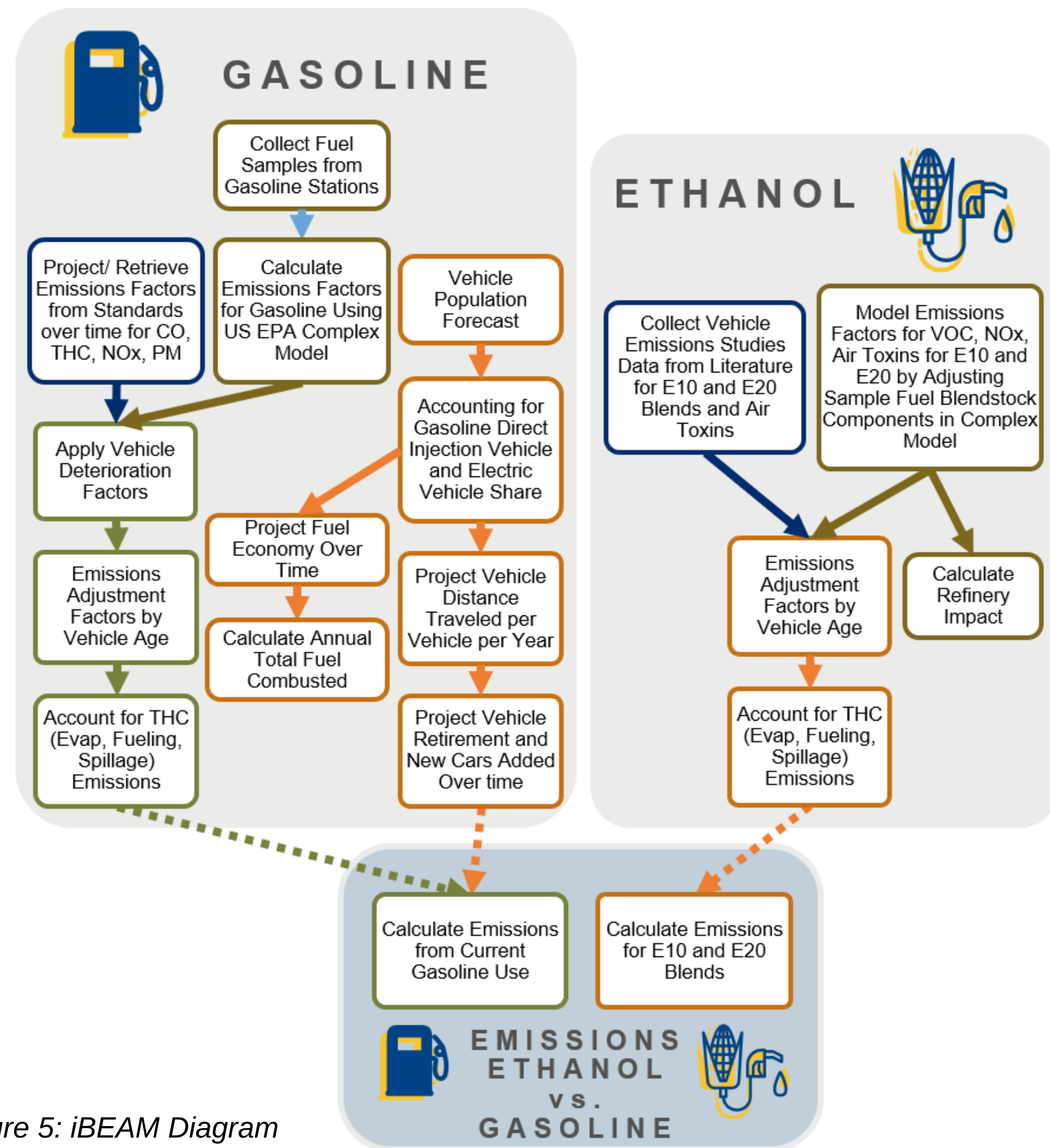


Figure 5: iBEAM Diagram

5. Setting Up the Model

5.1 Vehicle Characterization

Determining the vehicles on the road and their emission factors was the basis of the model. This section provides an overview of the vehicle characterization. Additional details and citations can be found in the full paper.

5.1.1 Determining Vehicle Population, Distance Traveled, and Fuel Economy

The impact of higher ethanol blends is highly dependent on the forecast of pollution generated by vehicle use and gasoline displaced by the incorporation of ethanol. The vehicle characterization includes a projection of the annual gasoline passenger cars on the road multiplied by the distance traveled by each car to calculate the total distance driven (in kilometers) in each city. This number is then multiplied by the emissions factors which are assessed in grams of pollutant per kilometer traveled to derive the total emissions from vehicles in a year.

To assess **vehicle population** using iBEAM in each city, the authors extrapolated historic data and vehicle saturation levels multiplied by projected population levels for each city. Next, a review of existing vehicle studies for the respective country and city provided additional data points. *Figure 6* shows the extrapolation of vehicle data for Beijing as an example.

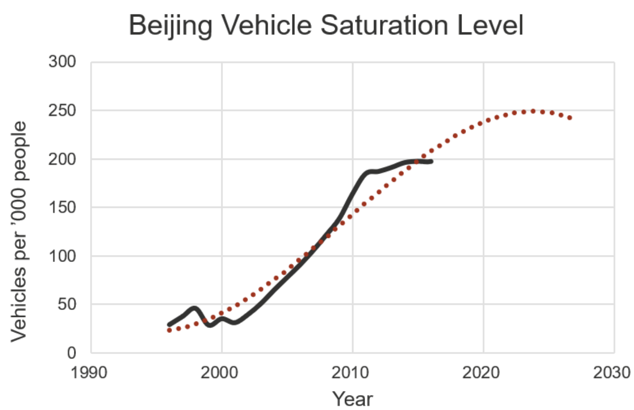


Figure 6: Example of Vehicle Population Estimation

The vehicle populations in the study cities were based on this approach. Total vehicles in all cities but Tokyo were projected to increase through 2027.

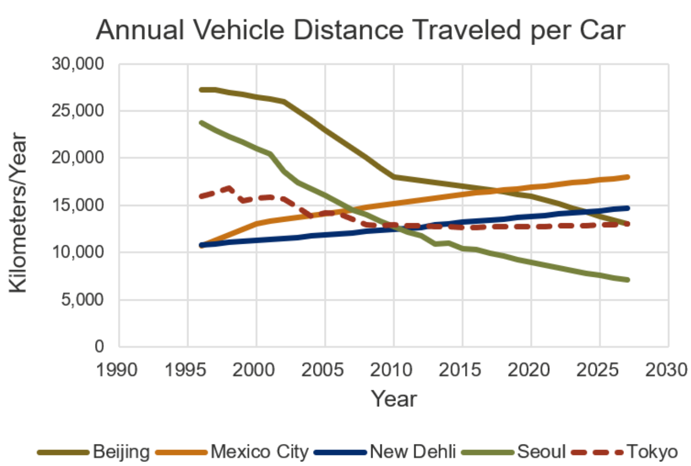


Figure 7: Summary of Annual Vehicle Distance Traveled by City

The **distance traveled per car** differed by city based on several factors, including the geographic expansion of the city boundaries and the development of public transportation systems. For example, past studies showed the average vehicle distance traveled in Mexico City increasing over the past years, and this trend seemed likely to continue with urban sprawl (Guerra 2014). Conversely, distance traveled in Seoul will decrease with the “greenbelt and newtown development” because commuting costs and travel distances will be significantly reduced (Jun 2012)

Finally, **fuel economy factors** were developed for each of the cities. These factors were necessary for the total fuel use and the subsequent emissions calculations. As technology advances and older cars are replaced with more efficient vehicles, the volume of fuel needed to drive 100 kilometers continues to decrease.

5.1.2 Electric Vehicle Share

The model accounted for the projected adoption of EVs, which will reduce the impact potential of ethanol blends by replacing gasoline vehicles with EVs. Increased interest in EVs has been widely discussed recently, a trend evident in various articles, press releases, and comments from industry leaders(Pham 2017; Arbib 2017; Modlin 2017).

The authors relied on regional outlooks (detailed in academic paper) for EV adoption goals in each city and/or country. Beyond these outlooks, the authors searched the literature for global EV adoption rate projections. A Whitmore 2016 study estimated the share of EV vehicles compared to all vehicles on the road at 4%, 7%, and 11% by 2027 for slow, moderate, and strong adoption policy regimes, respectively. These adoption rates appeared reasonable and were therefore incorporated into the model.

5.1.3 Vehicle Retirement

Vehicle retirement was also considered in the model; this increases the share of new vehicles in the vehicle pool, which will reduce overall emissions due to compliance requirements with the newest standards.

The iBEAM model adopted the retirement matrix concept in Argonne’s Vision model (Laboratory, n.d.). The Vision model estimates the number of cars on the road from each model year based on a year-over-year survival factor – which vehicles from a given year are still on the road the following year.

5.2 Gasoline Emissions Using the U.S. EPA Complex Model

Vehicle emissions factors were determined based on populating the U.S. EPA Complex Model with gasoline recipes derived from actual fuel samples from gasoline stations in the five cities.

5.2.1 Gasoline Sampling

To get a baseline recipe for current gasoline burned, three gasoline samples were taken in each city, and their compositions were analyzed to determine prevalent properties (octane, specific gravity, sulfur, RVP, oxygenates, etc.). The local gasoline composition determined from sampling served as an input to estimate the gasoline and blending recipes of each city.

It should be noted that refiners blend different oxygenates into gasoline to increase gasoline octane. MTBE, a prevalent oxygenate that has been phased out in the U.S.

due to its potential to contaminate ground water, is still blended in several studied countries. Japan uses ethyl-tert-butyl ether (ETBE) as an oxygenate. During sampling, large variations in MTBE levels occurred in gasoline samples in South Korea. Due to these variations, the baseline gasoline recipe utilized for analysis contained no MTBE for Seoul, but sensitivities for MTBE content were assessed.

5.2.2 Gasoline Blend Specifications

Gasoline blend specifications are typically set by each country to ensure gasoline properties meet specific requirements. One key specification is octane. Gasoline usually has two octane numbers that are standard measures describing how gasoline performs in an engine. The research octane number (RON) describes the behavior of the fuel in the engine at lower temperatures and speeds, usually in an attempt to simulate acceleration; the motor octane number (MON) describes the behavior of the fuel at high temperatures and speeds that simulate driving down a highway. Countries usually specify a range of RONs and an upper Reid vapor pressure (RVP), as well as limits on other gasoline characteristics (aromatics, olefins, etc.).

5.2.3 Methodology for Estimating Impact of Blending Ethanol

While gasoline sampling across the five cities provides many of the major gasoline properties, it is not sufficient to determine the recipe for gasoline blending – i.e., how much reformate, alkylate, butane, isomerate, FCC naphtha, etc. was used to produce the particular gasoline. This makes it difficult to determine the change in recipe from adding ethanol or replacing MTBE or ETBE with ethanol.

To work around this limitation, the study's authors established a base gasoline blend recipe for each city that used a linear programming model to match the properties of the gasoline samples collected. Each recipe also accounted for production of the gasoline at a hypothetical refinery with refining capacities representative of the particular country. Additionally, the authors set gasoline blending constraints to ensure recipes met legal requirements.

After establishing the base gasoline recipe for each city, a second recipe was generated by adjusting the first to include ethanol and remove MTBE or ETBE. The model added ethanol so that the final gasoline contained either 10 or 20 percent ethanol by volume. When incorporating ethanol, the model ensured key gasoline properties (octane and RVP) remained at the same values as the base gasoline. The model also made the appropriate adjustments to the refining process and equipment to maximize gasoline production (throughput) while meeting the required gasoline specifications (e.g., severity of the catalytic reforming unit, removing butane and pentanes, or adding butane, etc.).

After determining base and blended gasoline recipes for each city, the researchers estimated the emissions impact by looking at the change in emissions between the two gasoline recipes. These recipes were placed into the U.S. EPA's Complex Model, which remains the primary tool used by refiners to estimate key emissions components for compliance purposes.

5.3 Incorporation of Key Published Studies and Emissions Factor Adjustments

The authors conducted a thorough literature review of ethanol emission studies to incorporate the most relevant and up-to-date information in the iBEAM model.

5.3.1 Published Emissions Factors for NOx, THC, CO, and Selected Air Toxins

Numerous studies have been completed on the emissions factors for blended gasoline. *Table 3* summarizes the authors' extensive literature review of vehicle studies on E10 and E20 ethanol blends. The literature results generally show decreases for total hydrocarbons (THC) and non-methane hydrocarbons (NMHC), decreases for CO in higher ethanol blends, and less consistent data around NOx. The researchers relied on data from a study on gasoline direct injection engines for ethanol particulate matter (PM) emissions (M E Storey et al. 2010).

Table 3: Summary of Emission Factor Studies

Emission Averages	Ethanol-10	Ethanol-20
THC/NMHC - 10 studies	-21.9%	-21.5%
CO – 7 studies	-3.0%	-23.4%
NOx – 6 studies	-11.8%	-17.1%
PM	-6.0%	-36.0%
Benzene – 3 studies	-32.0%	-36.0%
Acetaldehyde – 3 studies	83.3%	101.0%
Formaldehyde – 3 studies	-24.9%	-36.0%
1,3 butadiene – 3 studies	-18.0%	-56.0%

5.3.2 Gasoline Exhaust Emissions Standards by City

For the study the authors assumed that all gasoline passenger cars follow the legally permissible emissions limits at present and future years. The authors used the reviewed standard values within their model.

Figure 8 depicts combined emissions standards for each city (HC plus NOx). All cities show reductions over time in permissible emissions, with Mexico City and New Delhi lagging behind in the earlier years.

Based on a review of the literature and published standards, the authors utilized these data points and the output emissions estimates from the recipes entered into the Complex Model to determine the estimated emissions of key pollutants.

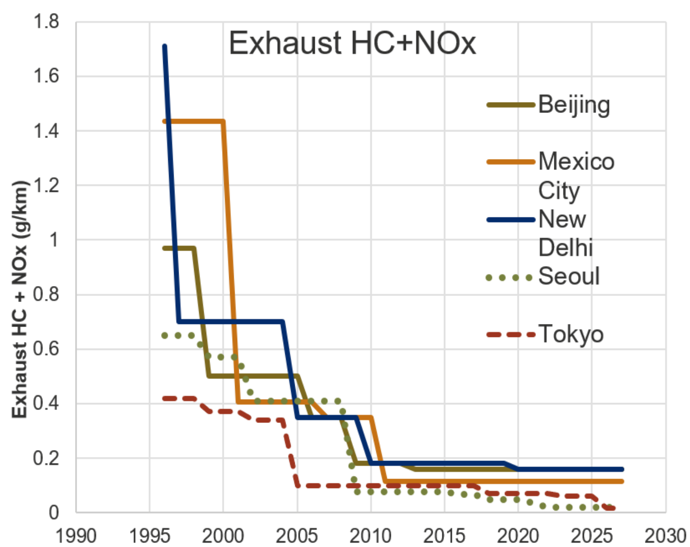


Figure 8: Summary of Exhaust HC+NOx Emissions Standards by City

5.3.3 Total Hydrocarbon Evaporative Emissions

In addition to tailpipe emissions, evaporative HC emissions – also known as gasoline vapors – were considered in calculating vehicle emissions. These emissions occur outside of the combustion cycle and include venting and leaks, permeation of fuel through the fuel system components, and emissions during vehicle fueling. *Figure 9* conceptually depicts evaporative emission sources from a vehicle.

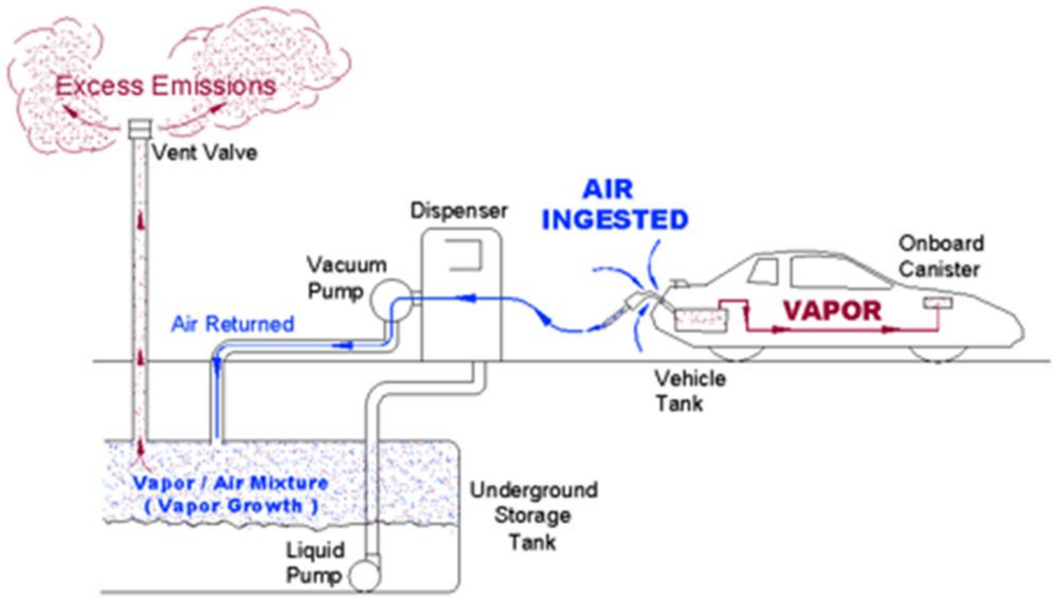


Figure 9: Evaporative Emissions Components (Source: California Air Resources Board)

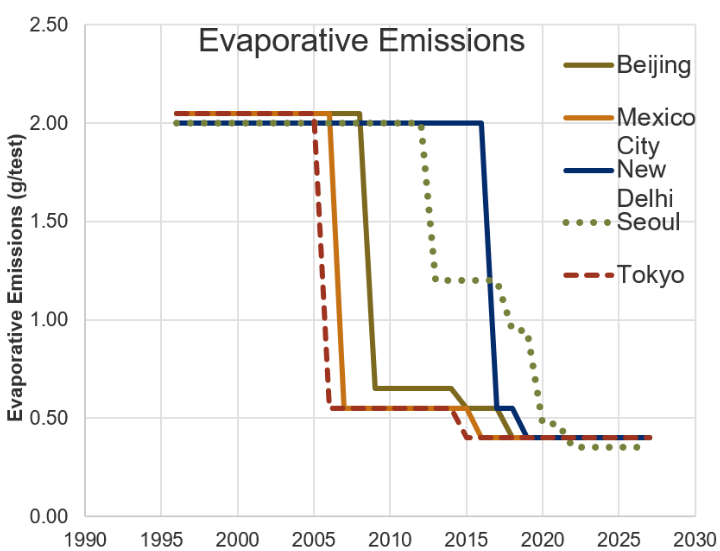


Figure 10: Summary of Evaporative Emissions Standards by City

Venting emissions (which include evaporation through the car's systems and losses from running the engine) are regulated by evaporative emission standards in each country. *Figure 10* shows the published standards for each city ("Transportpolicy.Net" 2017; Delphi, n.d.), which were incorporated into the study model.

Vehicle fuel systems emissions also include leaks and emissions occurring from permeation through fuel system materials such as hoses and gaskets. Leaks and permeation emissions were estimated from the MOVES model for each city and added as an input in iBEAM.

Refueling emissions occur when gasoline displaces vapors in the fuel tank. These vapors are either released into the atmosphere, captured with a Stage 2 vapor recovery unit at the fuel station, or captured with an onboard refueling vapor recovery (ORVR) system. Estimates of refueling emissions were calculated from the total vehicle fuel consumed (from fuel economy projections) along with the other evaporative emissions per liter of fuel.

5.3.4 Ethanol Emissions Factor Adjustments by Vehicle Age

As previously described, the authors characterized the vehicle set on the road for each city and a vehicle age emissions factor was also considered.

Based on vehicle fleets used in the reviewed vehicle emissions studies, the authors set up both a linear and non-linear adjustment option that allowed the model to account for an important nuance: different vintages of vehicles derive different levels of benefits from ethanol-blended fuels. In addition, the emissions factors developed from the U.S. EPA Complex Model for each city were included in the regression model. This ensured a city-specific contribution to the overall emissions assessment while considering the underlying vehicle fleet.

5.4 Estimating Positive Impacts of Ethanol Blending on Emissions

5.4.1 Total Weighted Air Toxins and Cancer Risk Assessment

The impacts of emissions on human health depend not only on the amount of emissions and particles in the air but also on the potential for damage to the human body of each type of emission. Past researchers compiled a report detailing the cancer potency factors for many chemical compounds, based on past cancer studies (Lloyd and Denton 2005). The relative potency factors used for this study for the four toxic air contaminants from gasoline combustion – 1,3-butadiene, benzene, formaldehyde, and acetaldehyde – are listed in *Table 4*.

Table 4: Lloyd and Denton Cancer Potency Factors

Toxic Air Contaminant	Relative Potency
Benzene	0.17
Acetaldehyde	0.016
Formaldehyde	0.035
1,3 butadiene	1

Higher levels of ethanol reduce engine emission of benzene and 1,3-butadiene but may increase acetaldehyde and under certain conditions formaldehyde. However, when factoring in the relative toxicity levels, 1,3-butadiene and benzene have much higher weights, and therefore the weighted sum risk of all four contaminants is lower in ethanol blends than in regular gasoline (Stein, Anderson, and Wallington 2013).

Additional pollutants of concern include PM emissions. These are small particles that pose serious health risks because they can get deep into human lungs, and some may even enter the bloodstream.

Aromatic hydrocarbons (i.e., benzene) found in regular gasoline have a higher double-bonded value and disproportionately contribute to PM formation. Therefore, increasing ethanol content (with ethanol's lower bonded values) tends to decrease PM (Aikawa and Jetter 2013). In the absence of PM emissions standards and in an effort to evaluate

PM emissions consistently for all five cities, the authors employed the PM emissions factors from a U.S. EPA MOVES 2014 study (Aldridge 2017) in iBEAM.

5.4.2 Gasoline Blending Results and Emissions Factor Results

Using country-specific blend specifications, past studies, and derived gasoline properties, the authors developed average emissions factors for gasoline in each city and under 0%, 10%, and 20% ethanol mix regimens. The thereby derived emissions improvements are presented in section 3.1 Reduced Emissions from Blending Creates Cleaner Air to Breathe of this document.

Results in all cities showed positive benefits for blending both E10 or E20. Both blends would decrease total VOCs and polycyclics, decrease or hold constant NOx emissions, and decrease all toxic exhaust emissions other than acetaldehyde, as it is produced during the partial oxidation of ethanol. Despite the increase of acetaldehyde, total weighted toxins from ethanol-blended gasoline showed a reduction in total cancer potency relative to base gasoline, due to the respective cancer potency factors of the individual toxic exhaust emissions. These findings demonstrate the pollution reduction benefits that cities would reap by blending ethanol.

5.5 Estimating Health Impacts from Ethanol Blending

5.5.1 Modeling Approach to Quantify the Health Impact from Blending

Cancer is a serious disease that adversely impacts the quality and length of patients' lives. Treatment of cancer incurs substantial healthcare costs, as well as individual and social costs associated with diminished quality of life, including lost income. To better characterize the impact of an ethanol fuel transition on patients and society, the authors estimated the expected years of life lost and the direct healthcare costs associated with the change in the number of cancer cases.

To understand these impacts, this section highlights the overall model, with details on how both lifetime cancer cases and health outcomes were calculated. Leveraging the results of the previously discussed Complex and iBEAM models, an additional three steps were completed across the five cities to illuminate these specific health impacts (*Figure 11*).

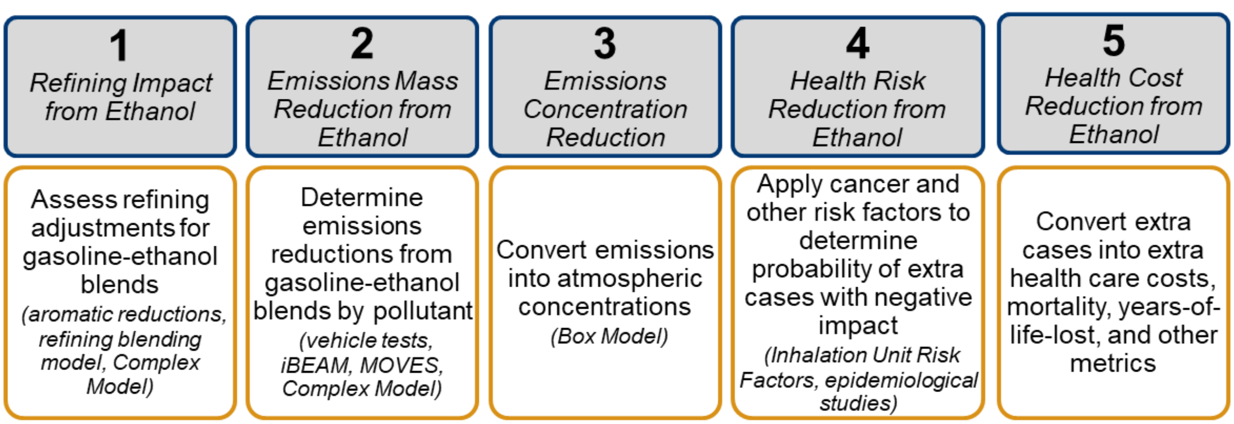


Figure 11: Health Impact Modeling Sequence

5.5.2 Refining Impact from Ethanol

The key pollutants assessed in the study that are directly impacted by blending and therefore affect health outcomes include acetaldehyde, benzene, benzo[a]pyrene (BaP), butadiene (1,3-butadiene), and formaldehyde, as well as carbon monoxide and particulate matter. Aromatic hydrocarbons, some of which are toxic compounds such as benzene, are added to gasoline because they have relatively high-octane values and serve as anti-knock agents in vehicle engines. With its a high-octane value and no aromatic compounds, ethanol can either substitute for or dilute aromatics in gasoline.

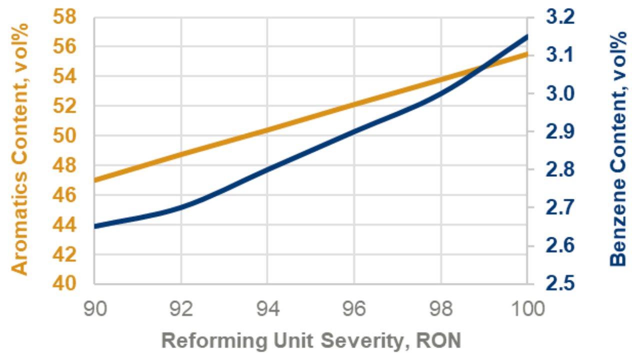


Figure 12: Aromatics Production at Refinery to Meet Octane Requirements

When ethanol is blended into gasoline, refiners can reduce the reforming unit severity (see section 5.7.1 Petroleum Refining Overview), while still meeting overall gasoline octane specifications. This lower RON results in lower benzene and aromatics content, as seen in *Figure 12.* The study aligns with a recent Fuels Trends Report stating: “Ethanol’s high-octane value has also allowed refiners to significantly reduce the aromatic content of the gasoline" (US EPA, n.d.).

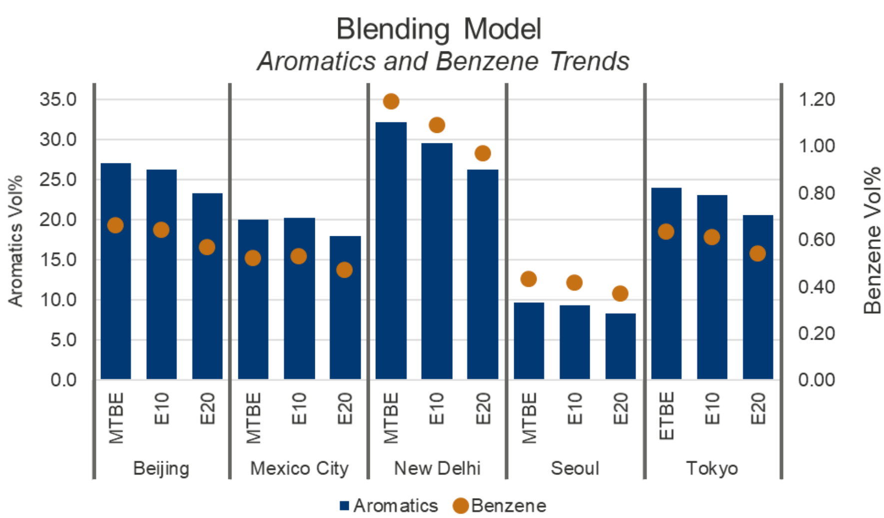


Figure 13: Projected Blending Behaviors for Refiners

Figure 13 displays predicted refiner blending behavior when ethanol is added to gasoline and a lower RON can be utilized. Seoul, Beijing, New Delhi, and Tokyo showed similar estimated reductions of benzene and aromatics in gasoline blends containing E10 and E20. For Mexico City, E20 follows the blending model pattern observed for all other cities. However, for E10 the blending model does not predict a decrease but about the same addition of aromatics as baseline gasoline. Despite this fact, accounting for the adjustments in throughput (see section 5.7.1 Petroleum Refining Overview for additional details), adding E10 still resulted in an overall reduction of predicted tailpipe emissions in Mexico City.

5.5.3 Converting Mass Emissions to Concentrations

Utilizing the derived emissions reductions from the previous models, the authors converted tonnes of pollutants into atmospheric concentrations using a box model. The box model calculated air changes for each city, taking into account the metropolitan areas (square meters), metrological mixing height (meters) wind speed (meters/second) ventilation rate (cubic meters per year), and air changes per year (#). Additional details on the box model can be found in the full paper.

Metrological conditions can significantly alter the relative emissions concentrations, even in simple box models. As shown in *Figure 14*, Beijing and Mexico City have about the same benzene emissions per year, but the higher air changes in Beijing result in overall lower concentrations in that city.

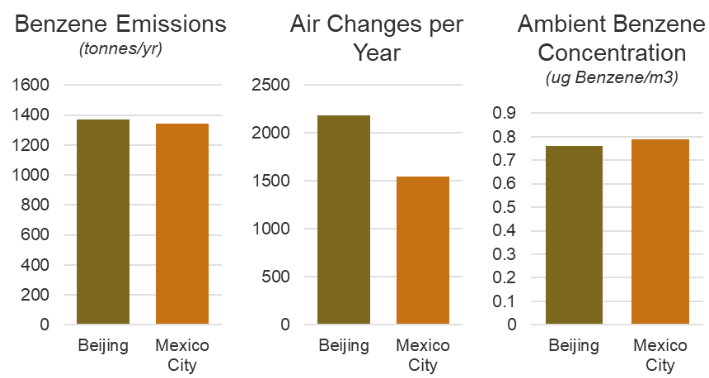


Figure 14: Box Model Relating Mass Emissions to Concentrations

The box model provided a good approximation of air concentrations. It should be noted that the box model is limited by its inability to reflect a) hot spots where higher population density areas within a city are exposed to higher emissions concentrations and b) geographic features, including mountains, etc. that affect air changes. The study applied a conservatively adjusted mixing height based on Pendergast 1974 and Schubert 1976. Additionally, the authors did not take into account population growth within the five cities, which will most certainly result in an underestimation of the derived health effects.

Estimating atmospheric concentrations allowed health risk factors to be applied in order to subsequently quantify the impact on lifetime cancer cases, health cost, and years of life lost.

5.5.4 Cancer Outcomes and Impacts

First for each of the five cities and the fuel scenarios, the average airborne pollutant concentration across the period of study (2016-2027) was calculated. Next, the mean impact of ethanol fuel (E10 and E20) on airborne pollutant concentrations was determined by taking the difference between the mean concentration for the ethanol fuel scenario and the standard gasoline scenario. This difference was assumed to represent the long-term average change in airborne pollutant concentrations with the reduction in inhalation exposure among the population. The approximate number of lifetime cancers cases avoided (or increased) was then estimated as the product of the difference in the airborne pollutant concentrations between the scenarios, the inhalation unit risk factor, and the population of the city.

Table 5: Inhalation Unit Risk (IUR) Factors

Toxic Air Contaminant	IUR Factor *(risk per ug/m³)*
Acetaldehyde	2.7 x 10^{-6}
Benzene	2.9 x 10^{-5}
Benzo[a]pyrene	1.1 x 10^{-3}
1,3 butadiene	1.7 x 10^{-4}
Formaldehyde	6.0 x 10^{-6}

The inhalation unit risk (IUR) factor is a standard metric for estimating excess lifetime cancer risk associated with inhalation exposure and assumes a lifetime of continuous exposure. Conservative IUR factors used in this study are shown in *Table 5* and were derived from the California Office of Environmental Health Hazard Assessment (OEHHA 2009).

The emission for the “possibly known carcinogen in humans” acetaldehyde is estimated to increase with the use of ethanol fuels (see section 5.4.1 Total Weighted Air Toxins and Cancer Risk Assessment for more detail), resulting in an increase in the estimated number of associated cancers. However, the increase from acetaldehyde cases is small relative to the reduction in cases linked to known carcinogens to humans, including benzene, butadiene, benzopyrene/polycyclics, and formaldehyde. Particularly noteworthy are the study results highlighting the magnitude of the percent change in predicted lifetime cancer cases by pollutant (*Figure 15*).

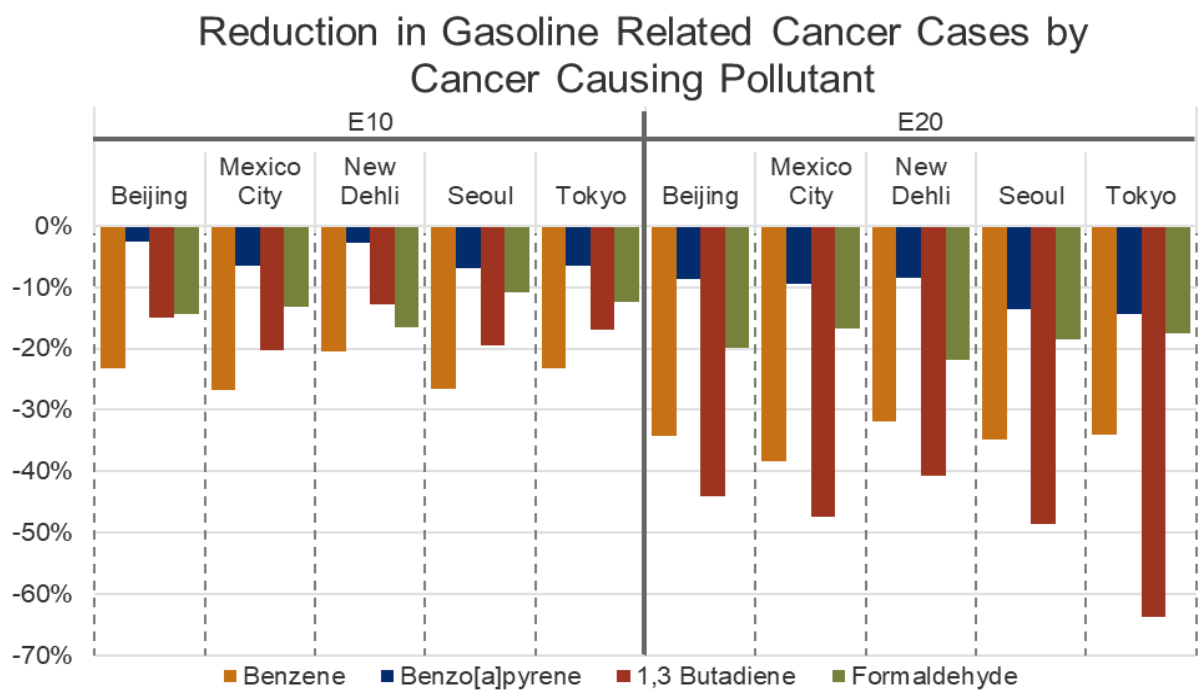


Figure 15: Change in Lifetime Cancer Cases by Pollutant

For each pollutant, the average years of potential life lost owing to different types of cancers were applied to all cities. This simplification treats each type of cancer as equally likely, and the treatment/ prognosis as uniform globally. In all cities, the transition to ethanol fuels is estimated to save thousands of years of potential life lost from exposure to these pollutants (*Table 6*).

Table 6: Change in years of potential life lost or gained by pollutant

	Acetaldehyde	Benzene	Polycyclics	1,3-Butadiene	Formaldehyde	Total
			E10			
Beijing	76	-1,135	-487	-1,667	-48	-3,262
Delhi	57	-1,375	-951	-1,835	-32	-4,136
Mexico City	154	-1,770	-692	-2,431	-138	-4,877
Seoul	43	-488	-641	-1,422	-20	-2,529
Tokyo	40	-566	-676	-1,303	-21	-2,527
			E20			
Beijing	200	-1,671	-1,583	-4,894	-67	-8,015
Delhi	156	-1,967	-1,357	-4,286	-40	-7,494
Mexico City	401	-2,767	-1,521	-7,775	-182	-11,843
Seoul	106	-638	-1,259	-3,537	-35	-5,363
Tokyo	106	-828	-1,486	-4,918	-30	-7,155

Note: Negative values indicate that the change to ethanol fuel will save years of potential life lost.

Cancer treatment incurs substantial costs of the healthcare system. The authors did not identify standardized global data for the individual costs of cancer treatment, though it was clear that treatment costs vary widely among cancers and countries. A conservative estimate that each cancer case requires $70,000 in treatment costs was assumed, given the pollutants considered in this study predominantly cause lymphohematopoietic and lung cancers (Mariotto et al. 2011). Changes in direct cancer treatment costs are depicted in *Figure 16.*

Ethanol fuels are predicted to reduce ambient concentrations and the number of excess cancers across all cities, thus saving millions of dollars in cancer treatment costs to the healthcare system relative to continued use of current gasoline, as seen in the Key Results Section.

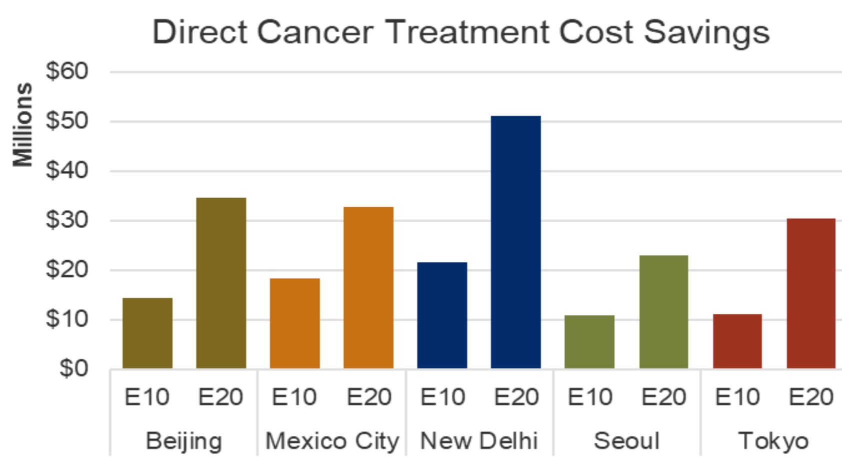


Figure 16: Change in Direct Cancer Treatment Costs

5.5.5 Summary of the Health Impact Assessment

Overall, the introduction of ethanol fuels is estimated to yield a net reduction of approximately 200-300 cancer cases per city, associated with several of the key pollutants in vehicle exhaust. Avoiding these cancers will save several thousand years of potential life lost due to premature death in each city and an additional tens of millions of dollars of direct healthcare costs for treatment, beyond the adverse impacts to quality of life, loss of income, and devastation to families.

To put these changes in perspective, 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 U.S. to 1 ppm, the Occupational Safety and Health Administration estimated this reduction would avoid approximately 1.3 cancers per year at a cost estimated to be $2.3 million per cancer avoided per year (Federal Registry 1996). By contrast, the health benefit of ethanol fuels in these five cities is significant relative to the total burden of disease, which suggests that transitioning to ethanol fuels will demonstrably benefit public health.

5.6 Greenhouse Gas Life-cycle Emissions Savings from E10 and E20 Blends

The study assessed GHG emissions on a life-cycle basis for ethanol produced and shipped from the U.S. to each of the five studied cities and blended on location into E10 and E20 gasolines. These emissions were then compared to current gasolines produced in the countries.

The model calculated the results by city, life-cycle model, and ethanol blend. Researchers energy-weighted each component of the gasoline currently used to determine the GHG value of these baseline gasolines. These fuels are a blend of either gasoline and MTBE, gasoline and ETBE, or gasoline without an oxygenate.

The generated values were then compared to the GHG emissions of the finished E10 and E20 fuels, which were derived by proportionally blending the imported U.S.-produced ethanol with each country's baseline gasoline. Note that additional GHG reductions likely to occur from streamlined refinery operations in each country were not considered due to modeling complexity. Therefore, the study produced a conservative estimate of total savings.

The study calculated the GHG emissions based on data from two life-cycle models within iBEAM:

1) The GREET model developed by Argonne National Laboratory is the gold standard for U.S.-based life-cycle analysis and contains the most up-to-date information on corn ethanol production. The authors selected a California version of the GREET model because it incorporates the Low Carbon Fuel Standard.
2) The BioGrace model is a European life-cycle model that evaluates European fuel pathways under the Renewable Energy Directive (RED).

The need to assess the GHG emissions utilizing both the GREET and the BioGrace models stems from slightly different assumptions around crude oil production and refinery configuration. Rather than rely on one model, the authors assessed GHG emissions with both models and attained very similar results, as shown in the full paper.

5.6.1 GHG Emissions of U.S.-produced Ethanol Shipped to Each City

The iBEAM model follows a typical carbon-equivalent analysis that accounts for the main GHGs, including carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O)

described in a common unit. The model displays the energy inputs and emissions from corn ethanol over its life cycle, from farming to end use.

For the life-cycle analysis model, the carbon in the corn itself was treated as carbon neutral – absorbed during plant growth and later released in the final product. Emissions accounted for from farming included farming energy, fertilizer inputs, N_2O emission from nitrogen fertilizer and crop residue, and corn transport to the plant. Ethanol plants produce ethanol and dried distillers grains (DGS), and a coproduct credit for DGS can be calculated based on its value as animal feed. Plant input parameters such as ethanol and DGS yield per bushel, electricity, natural gas, chemicals and enzymes and a loss factor were included for emissions calculations. Energy intensity for transportation were accounted for in the model, with transportation distances changed to reflect the GHG emissions incurred during shipment of ethanol to the target cities

To incorporate this type of life-cycle analysis into the iBEAM model, three analysis approaches were adjusted and then configured into the model (GREET substitution, GREET allocation, and BioGrace allocation), with the results from the GREET allocation method displayed in section 3.2 Ethanol's Lower GHG Emissions Decreases Environmental Damages of this document. The GREET model with energy allocation means the total life-cycle emissions are distributed based on an energy allocation factor of ethanol relative to the total energy content of all products produced at the ethanol plant (ethanol+DGS). The model incorporates the many input parameters as mentioned to best reflect the production of ethanol from field to end use.

GREET also estimates the emissions from refining crude oil into gasoline, based on the complexity of the oil refineries, as well as the density of crude oil sourced from different oil fields around the world. These parameters were considered when establishing the baseline GHG emissions from the current gasoline in each country. A comparison was then drawn to emissions from ethanol-blended gasoline to identify any differences.

5.6.2 GHG Modeling Results

The GHG emissions from ethanol production and blending were compared with the gasoline/oxygenate blends by city, life-cycle model, and ethanol blend. The study derived the cumulative GHG savings for each ethanol blend through 2027 from the total fuel use in each city. Regardless of the model used for the analysis, the authors saw very similar results showing decreases in total GHG emissions from ethanol blends, thus benefiting the environment.

5.7 Refining Impact of E10 and E20 Deployment in Each Country

5.7.1 Petroleum Refining Overview

The processing steps in petroleum refining are primarily designed to convert crude oil into transportation fuels. The refining process is complex and highly technical, and the full paper outlines a complete flow chart and definitions. This summary simply focuses on the key steps influenced by blending ethanol.

One of the key components in the refining process relevant to ethanol blending is the catalytic reforming unit. The catalytic reforming unit processes heavy naphtha – a major component of crude – into high octane for gasoline blending. The severity (research octane number or RON) of the catalytic unit is adjusted to meet overall gasoline octane specifications for finished gasoline resulting from blending all gasoline components. Higher severity (RON) results in more octane, hydrogen, and aromatics but less total volume (throughput).

When oxygenates like ethanol are added, there is less need for high octane from the catalytic reforming unit, so the severity (RON) of the catalytic reforming unit can be reduced and/or more crude components can bypass the catalytic reforming unit and be blended directly to gasoline. The result is more gasoline production (throughput) as a result of adding oxygenates. However, by operating at lower severity and processing less total volume, there is less hydrogen produced from this unit. A refinery producing gasoline with high blends of ethanol will need to replace the hydrogen production lost from the catalytic reforming, which is usually done by converting natural gas or refinery fuel gas into hydrogen.

Properties of gasoline can change when oxygenates are added to gasoline. This includes ethanol, which can increase gasoline vapor pressure (Reid vapor pressure or RVP). MTBE and ETBE – two commonly used oxygenates – have RVPs close to finished gasoline, and thus their addition results in little or no need for butane or pentane removal to meet gasoline RVP specifications. Ethanol has a much larger impact on RVP, and it is generally necessary to remove butane and sometimes even pentanes to meet the RVP requirements for gasoline.

To summarize, the key changes in the refining process to accommodate ethanol primarily revolve around two adjustments. First, the lower processing intensity increases total volume of gasoline production with the same amount of crude input. Second, a reduction in hydrogen production may need to be offset. Finally, it is also possible that additional refinement will be needed to meet gasoline specifications (i.e., RVP) when blending. To calculate any changes in refinery profits, the study's model accounted for these changes based on country-specific recipes and gasoline refining characteristics.

5.7.2 Calculating Refinery Profits

After adjusting the various components and refining process based on the gasoline recipes from the country samples and information from past studies, the authors estimated refiner profits. The incremental changes in hydrogen and gasoline production determined changes in refining profits per barrel across each of the five cities. Both the gasoline price and the natural gas price were used for the estimation, and the assumed prices were based on averages between July 2016 and July 2017 from the U.S. Energy Information Administration (EIA). The study also estimated additional operating costs for a hydrogen plant, which is needed when blending occurs.

Across all cities, ethanol-blended fuels returned equal or increased revenue for refiners for E10 and E20. Results can be found in section 3.3 Blending Ethanol Increases Refining Profits of this document.

6. Summary

The findings of this study – *The Impact of Higher Ethanol Blend Levels on Vehicle Emissions in Five Global Cities* – illuminate the benefits of higher ethanol blends, including:

1. **Human health benefits** from reduced air toxin emissions when ethanol is part of a pollution strategy
2. **Environmental benefits** of replacing high-polluting, carbon-intense gasoline components with ethanol
3. **Economic benefits** to fuel refiners through strategies that include blending ethanol

Carefully examining the impacts of ethanol blending on human health, the environment, and refinery profits shows that the decision to support higher blends can lead to benefits across many aspects of life, both now and into the future.

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Terms and Acronyms

CO	Carbon monoxide
E10	10% of final gasoline mixture is anhydrous ethanol, while 90% is crude-based gasoline
E20	20% of final gasoline mixture is anhydrous ethanol, while 80% is crude-based gasoline
EPA	U.S. Environmental Protection Agency
ETBE	Ethyl-tert-butyl ether
EV	Electric vehicle
GHG	Greenhouse gas
GREET	Greenhouse gases, Regulated Emissions and Energy use in Transportation
HC	Hydrocarbon
iBEAM	International Biofuels Emissions Analysis Model
IUR	Inhalation Unit Risk factor estimates excess lifetime cancer risk associated with inhalation exposure
MON	Motor octane number
MTBE	Methyl tert-butyl ether
NOx	Nitrogen oxide
PM	Particulate matter
RON	Research octane number
RVP	Reid vapor pressure
THC	Total hydrocarbons
VOC	Volatile organic compounds

Works Cited

Aikawa, Koichiro, and Jeff J Jetter. 2013. "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* 15 (3): 298–306. https://doi.org/10.1177/1468087413481216.

Aldridge, M. 2017. "Light-Duty PM Emission Rates Update." https://www.epa.gov/sites/production/files/2017-04/documents/04_-_light-duty_pm_emission_rates_update.pdf.

Arbib, J. 2017. "Rethinking Transportation 2020-2030." RethinkX. https://static1.squarespace.com/static/585c3439be65942f022bbf9b/t/591a2e4be6f2e1c13df930c5/1494888038959/RethinkX+Report_051517.pdf.

Baan, Robert, Yann Grosse, Kurt Straif, Béatrice Secretan, Fatiha El Ghissassi, Véronique Bouvard, Lamia Benbrahim-Tallaa, et al. 2009. "A Review of Human Carcinogens—Part F: Chemical Agents and Related Occupations." *The Lancet Oncology* 10 (12): 1143–44. https://doi.org/10.1016/S1470-2045(09)70358-4.

Delphi. n.d. "Worldwide Emissions Standards - Passenger Cars and Light Duty, 2016|2017."

Federal Registry. 1996. "Occupational Exposure to 1,3-Butadiene. Final Rule. Federal Register 61: 56746-56856."

Guerra, Erick. 2014. "The Built Environment and Car Use in Mexico City: Is the Relationship Changing over Time?" *Journal of Planning Education and Research* 34 (4): 394–408. https://doi.org/10.1177/0739456X14545170.

IARC. 2012. "IARC Monographs Volume 100F. Chemical Agents and Related Occupations." Lyon: France.

Jun, Myung-Jin. 2012. "The Effects of Seoul's Greenbelt on the Spatial Distribution of Population and Employment, and on the Real Estate Market." *The Annals of Regional Science* 49 (3): 619–42. https://doi.org/10.1007/s00168-011-0461-5.

Laboratory, A.N. n.d. "Vision Model." http://www.anl.gov/energy-systems/project/vision-model.

Lloyd, Alan C., and Joan E. Denton. 2005. "Air Toxics Hot Spots Program Risk Assessment Guidelines Technical Support Document for Exposure Assessment and Stochastic Analysis." https://oehha.ca.gov/media/downloads/crnr/may2005hotspots.pdf.

M E Storey, John, Teresa L Barone, Kevin M Norman, and Samuel Lewis. 2010. *Ethanol Blend Effects On Direct Injection Spark-Ignition Gasoline Vehicle Particulate Matter Emissions*. Vol. 3. https://doi.org/10.4271/2010-01-2129.

Mariotto, Angela B., K. Robin Yabroff, Yongwu Shao, Eric J. Feuer, and Martin L. Brown. 2011. "Projections of the Cost of Cancer Care in the United States: 2010–2020." *JNCI Journal of the National Cancer Institute* 103 (2): 117–28. https://doi.org/10.1093/jnci/djq495.

Modlin, R. 2017. "Op-Ed: Combustion Engines Are Not Going Anywhere for Quite A While," August 16, 2017. http://www.governorsbiofuelscoalition.org/op-ed-combustion-engines-are-not-going-anywhere-for-quite-a-while/.

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."

Pham, S. 2017. "Volvo: Gas-Only Cars Are History after 2019." *CNN*, July 5, 2017. https://money.cnn.com/2017/07/05/autos/volvo-electric-cars-internal-combustion-engine/.

Stein, Robert A., James E. Anderson, and Timothy J. Wallington. 2013. "An Overview of the Effects of Ethanol-Gasoline Blends on SI Engine Performance, Fuel Efficiency, and Emissions." *SAE Int. J. Engines* 6 (1): 470–87. https://doi.org/10.4271/2013-01-1635.

"Transportpolicy.Net." 2017. 2017. https://www.transportpolicy.net/.

US EPA. 2017. "Toxicological Review of Benzo[a]Pyrene: Executive Summary. EPA/635/6-17/003Fc." https://cfpub.epa.gov/ncea/iris/iris_documents/documents/subst/0136_summary.pdf.

———. n.d. "Integrated Risk Information System Chemical Assessment Summary: Acetaldehyde." https://cfpub.epa.gov/ncea/iris/iris_documents/documents/subst/0290_summary.pdf.

———. n.d. "United States Environmental Protection Agency Fuel Trends Report: 2006-2016 (Released October 2017)." https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P100T5J6.pdf.

Whitmore, A. 2016. "How Fast Could the Market for Electric Vehicles Grow?" *Energy Post*, June 21, 2016. http://energypost.eu/fast-market-electric-vehicles-grow/.

Yabroff, K. Robin, Cathy J. Bradley, Angela B. Mariotto, Martin L. Brown, and Eric J. Feuer. 2008. "Estimates and Projections of Value of Life Lost from Cancer Deaths in the United States." *Journal of the National Cancer Institute* 100 (24): 1755–62. https://doi.org/10.1093/jnci/djn383.