The Impact of Higher Ethanol Blend Levels on Vehicle Emissions in Five Global Cities

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Vehicle Emissions in Five Global Cities
University of Illinois at Chicago Energy Resources Center
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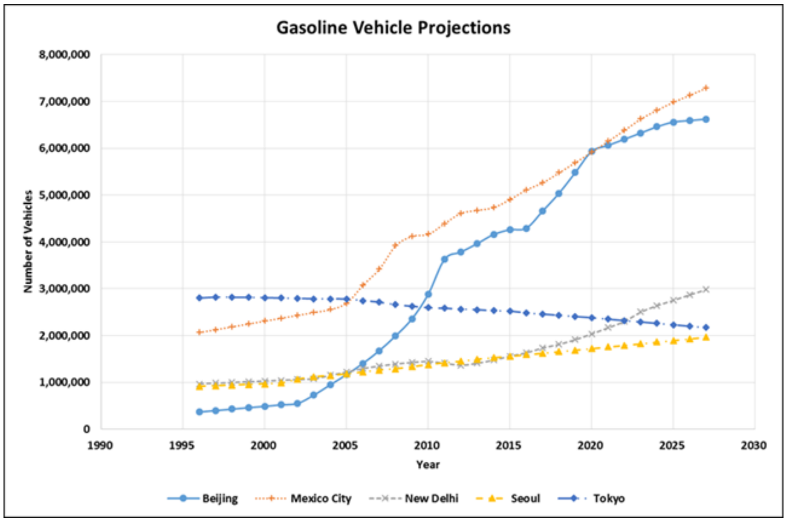
Executive Summary

This study examines the tailpipe and greenhouse gas emissions savings from the use of ten and twenty percent ethanol blends in five mega cities around the world including Beijing, Delhi, Seoul, Tokyo, and Mexico City. The unique feature of the study is that it explores the comprehensive environmental linkages from fuel production through health impact. It takes into account: a) the regionally specific fuel blending requirements to meet local fuel specification, b) the calculated tailpipe emissions reductions in the local vehicle fleet and the local vehicle technology, c) the concentration reductions in the local atmosphere from the reduced tailpipe emissions, d) the localized health impact and treatment cost.

The model results indicate that ethanol added to gasoline will alter the gasoline formulation towards lower aromatic fuels and lower tailpipe emissions resulting in health benefits such as reduced cancer rates and health care costs. The benefits of such policies can be explored in conjunction with other clean transportation policies such as stricter fuel economy standards or electrification deployed separately or in combination.

The results of the study are based on a spreadsheet based model termed the International Biofuels Emissions Analysis Model (iBEAM). This model was developed in order to facilitate the exploration of many likely blending, emissions, and electric vehicle (EV) adoption scenarios in an open and transparent way while incorporating data from the latest ethanol-gasoline blend vehicle emissions studies.

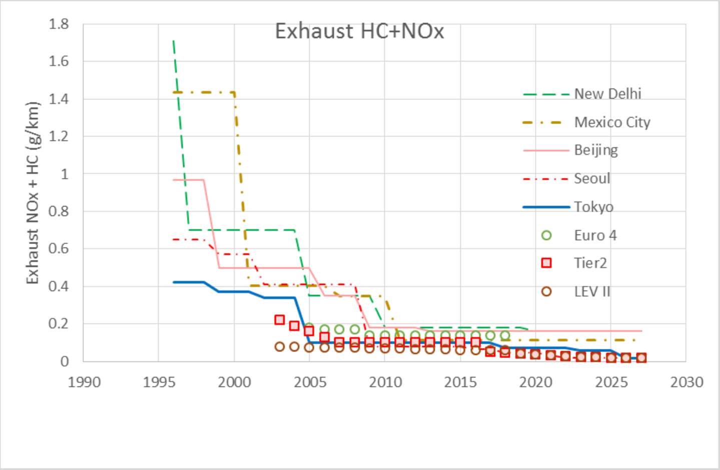


Tailpipe Emissions

The iBEAM model consists of a vehicle characterization module which is combined with an emission factor assessment for both gasoline and ethanol to derive total emissions adjustments from ethanol blended gasoline. In the model the projected passenger car population takes into account a) the projected electric vehicle share and b) the annual new car additions and replacement of retired vehicles.

The emissions factors for both gasoline and ethanol are assessed in two different ways:

- Emissions Factors for Gasoline from Complex Model. In this case we ran the US EPA Complex Model with country specific gasoline samples to derive emissions factors for gasoline.



- Emissions Factors for Ethanol from Complex Model. A base gasoline was established for each city that met the properties of the gasoline samples followed by a modeled adjustment of the gasoline blend stocks from ethanol blending.

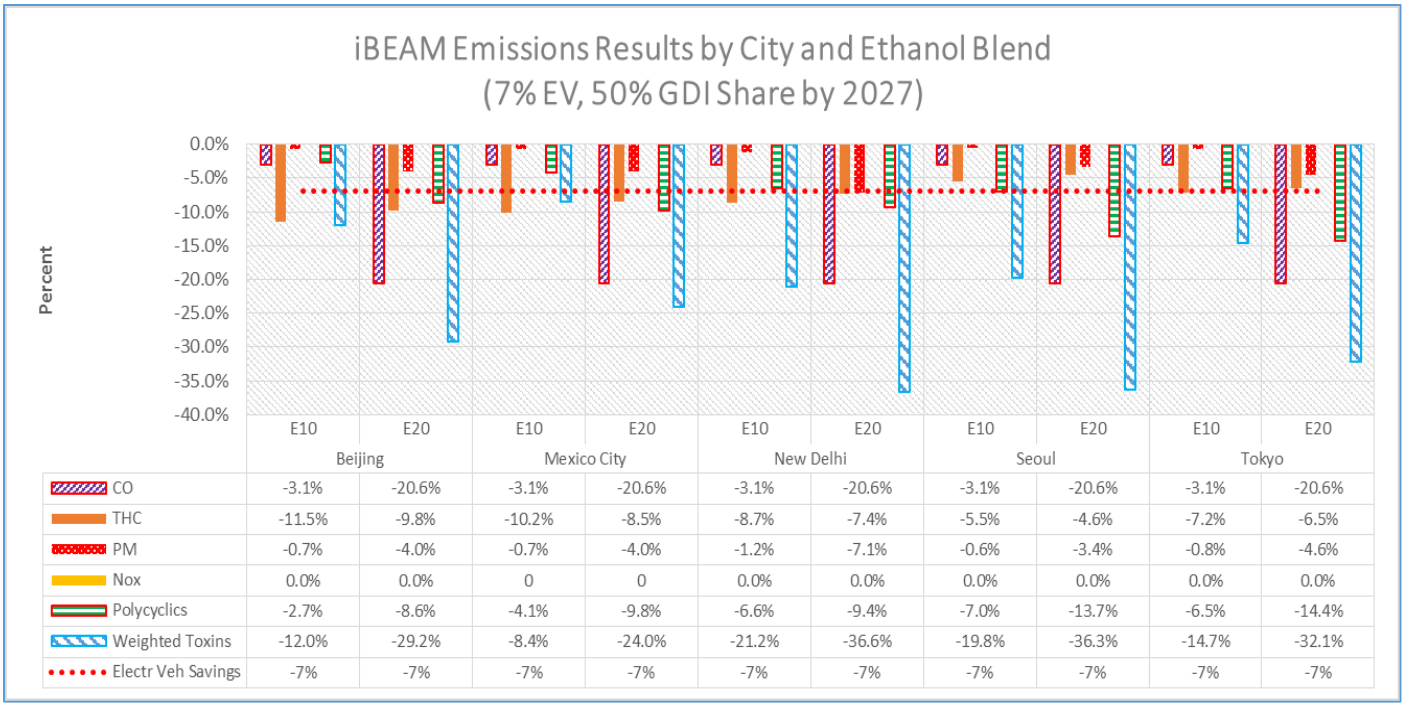
- Emissions Factors for Gasoline from past and future emissions standards. The past, current, and future emissions standards governing each city was surveyed for each city. The standards specify the emissions limits set for gasoline passenger vehicles for the applicable test protocols.

- Emissions Factors for Ethanol from published vehicle emissions studies. We surveyed the literature for substantially all major gasoline-ethanol vehicle emissions studies (for E10 and E20) and summarized the expected impact from ethanol on combustion emissions.

- For hydrocarbon emissions from gasoline and ethanol the effects of altitude and reid vapor pressure on evaporative emissions were added as well as an explicit representation of refueling losses, permeation, spillage, and onboard refueling vapor recovery (ORVR) technologies.

On a total tonnage and percentage basis through the year 2027 the results show hydrocarbon (THC, VOC) reductions across all cities from E10 and E20 blends which should result in reduced risk for ozone formation in these cities. Furthermore, the study finds significant polycyclics and weighted toxins reductions (often correlated with cancer) and reduced CO emissions which reduces heart disease and other health effects. The study also shows that NOx emissions remain unaffected by ethanol blends.

The results are also particularly relevant in light of the current debate on electric vehicle deployment. Since iBEAM enables a selection of different EV adoption scenarios we can compare the emissions savings from ethanol blends to the emissions savings expected with EVs. Note that these are tailpipe emissions only and do not include any upstream emissions from electricity production which, in many of the studied countries, may come from coal fired power plants. The comparison between ethanol and EV (dashed red line in graph below) shows that EV vehicles through 2027 will just barely save the same amount of THC/VOC emissions as a fleet change to E10 and E20 would produce and that EV vehicles will provide significantly less savings for carbon monoxides and weighted toxins through 2027.



	Beijing		Mexico City		New Delhi		Seoul		Tokyo	
	E10	E20	E10	E20	E10	E20	E10	E20	E10	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%
▬ Nox	0.0%	0.0%	0	0	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
▭ 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%
•••••• Electr Veh Savings	-7%	-7%	-7%	-7%	-7%	-7%	-7%	-7%	-7%	-7%

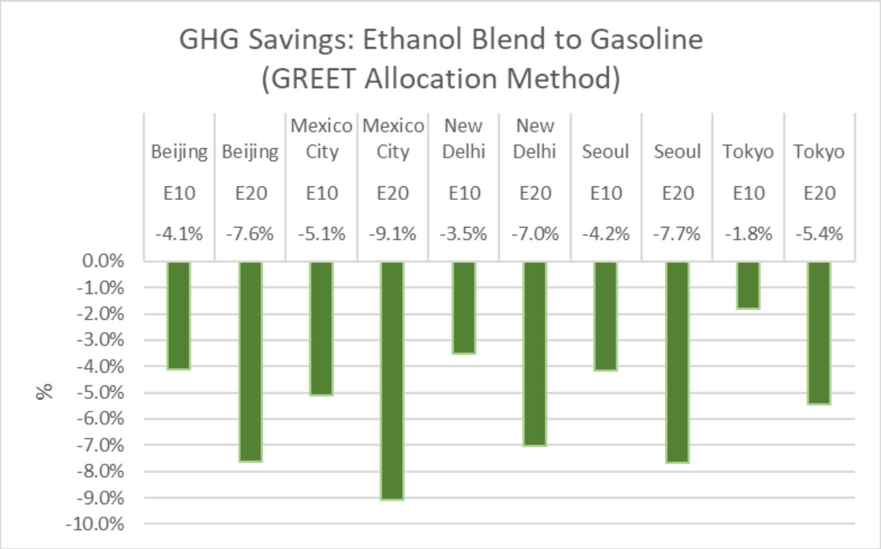
	Beijing		Mexico City		New Delhi		Seoul		Tokyo	
	E10	E20	E10	E20	E10	E20	E10	E20	E10	E20
CO	-69,613	-462,832	-94,806	-630,332	-21,844	-145,236	-15,004	-99,754	-21,480	-142,811
THC	-29,238	-24,866	-25,953	-21,593	-9,842	-8,353	-3,562	-2,968	-5,137	-4,581
PM	-10	-58	-11	-69	-6	-35	-1	-8	-4	-23

Greenhouse Gas Emissions

The GHG module in iBEAM calculates the GHG emissions based on data from two life cycle models:

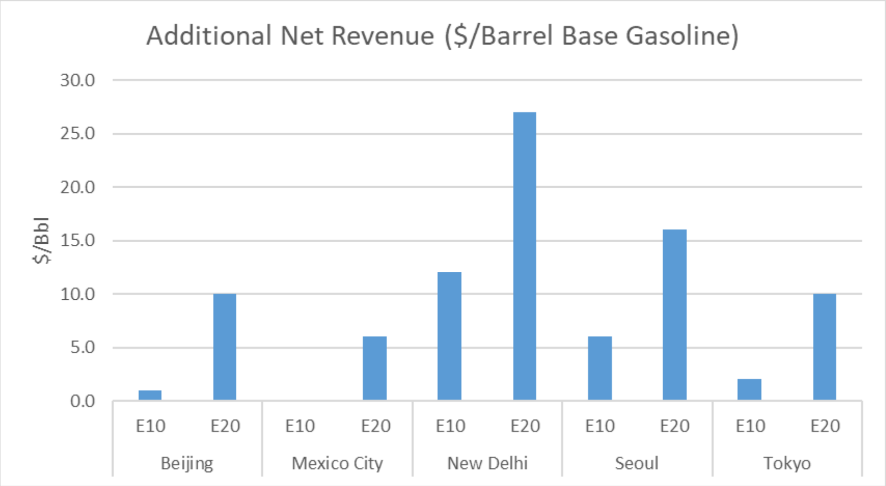
1) The GREET model developed by Argonne National Laboratory which is the gold standard for U.S. based life cycle analysis and contains the most up to date information on corn ethanol production. A California version of the GREET model is used for the Low Carbon Fuel Standard. An earlier version was used by the US Environmental Protection Agency for the Renewable Fuel Standard modeling.
2) The Biograce Model is a European life cycle model that evaluates European fuel pathways under the Renewable Energy Directive (RED). Current Japanese modeling efforts are also closely aligned with the EU RED methodology.

On a total tonnage and percentage basis the study shows sizable greenhouse gas reductions for all cities and ethanol blends. Cities with high fuel demand and current MTBE use can realize large GHG savings due to the high GHG intensity of the MTBE production pathway. Beijing and Mexico City, for example, can save 10 and 15 million metric tonnes of CO_2 emissions, respectively, from E10 blends through 2027.



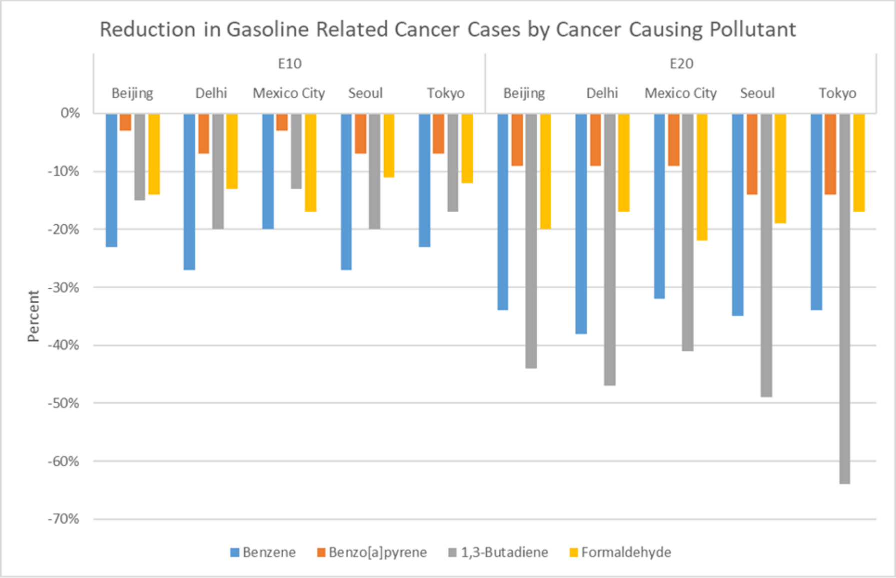
Refinery Profitability

We assessed the financial impact on refiners serving our studied cities from accommodating E10 and E20 in their blend stocks. When oxygenates (like ethanol in E10 or E20) are added in gasoline blending, there is less need for octane from the catalytic reforming unit within a refinery and more hydrotreated naphtha feed to the catalytic reforming unit can be bypassed and blended directly to gasoline. The result is more gasoline production. However, as a result of operating at lower severity and processing less feed, there is less hydrogen produced from this unit for use in other plant processes . Based on our assessment of each country's refinery profile we determined the incremental hydrogen and incremental gasoline production and net revenue impact resulting from accommodating E10 and E20 in the blends. The net revenue was calculated on the basis of dollar per barrels of base case gasoline for each city. The results show that all ethanol blended fuels return equal or increased revenue for refiners.



Health Impact

The introduction of ethanol fuels was estimated to yield a net reduction of approximately 200-300 cancers per city, associated with several of the key pollutants in vehicle exhaust relative to continued use in gasoline, and varying among cities and between ethanol fuel blends. Avoiding these cancers will save several thousand years of potential life lost in each city and an additional tens of millions of dollars of direct healthcare costs for cancer treatment. The impact of cancer, however, is much greater than these metrics, as cancer adversely impacts the quality of life, can lead to loss of income, and devastates families. For example, in the US, a person-year of life lost has been valued at $150,000 which leads our assessment to show several hundred million dollars of savings from ethanol blends.



In summary adding E10 or E20 to the fuel supply in each of studied city significantly reduces key pollutants and especially air toxins and polycyclic hydrocarbons with quantifiable positive health impacts. Linear Refinery Programming showed that these ethanol blends given each country's refinery structure can be produced with additional profits to the refining sector.

1 Introduction

The purpose of this study coauthored by the University of Illinois at Chicago (UIC) Energy Resources Center is to assess the cumulative future tailpipe and greenhouse gas emissions benefits from adopting higher ethanol blends for the light duty vehicle market in light of current and predicted fuel demand for five major global cities. The study also assesses refinery profitability considerations associated with producing these fuels. The five cities of interest are Beijing, Mexico City, New Delhi, Seoul, and Tokyo, all of which face major air quality challenges.

In the United States the blending of ethanol at 10% and 15% (E10 and E15) in conventional vehicles and at higher blends (in flex fuel vehicles) has been accompanied by a dramatic reduction in air emissions across altitudes and throughout all driving seasons [1]. Together with Brazil and Europe a large amount of experience and data has been accumulated to document the benefits of introducing ethanol into the fuel supply.

The scenarios in the present study include the quantification of emissions differences between current gasoline use without ethanol compared to higher ethanol blends including E10 and E20. It is expected that the growing use of hybrid electric vehicles and fully electric vehicles (EVs) will eventually impact the demand for gasoline and ethanol, and therefore this trend will also be forecasted here through 2027.

Models that assess the contributions of vehicle tailpipe emissions from different ethanol gasoline blends would ideally incorporate emissions factors for different regional driving and traffic conditions, different vehicle vintages and market shares, altitude and climate effects, and the respective baseline fuel compositions. One such model, the US Environmental Protection Agency's MOtor Vehicle Emission Simulator (MOVES) is an emission modeling system that estimates emissions for mobile sources at the national, county, and project level for pollutants. However, MOVES is not set up to assess emissions from ethanol blends greater than E15 and its handling of ethanol blends E10 and E15 has received criticism [2] [3] [4] [5].

While MOVES has powerful databases the calculation of the data in a "black box" makes the interpretation of the results often difficult. Moreover, while a recent effort was made to adjust MOVES for Mexico the country-specific adjustment resorts often to basic recalibration factors which adds another level of uncertainty to the results.

In order to facilitate the exploration of many likely blending, emissions, and EV adoption scenarios in an open and transparent way we have developed a spreadsheet based model termed the International Biofuels Emissions Analysis Model (iBEAM).

> For tailpipe emissions assessments this model allows us to incorporate data from the latest ethanol-gasoline blend vehicle emissions studies, while still taking key emissions aspects such as vehicle retirement and emissions control deterioration effects over time into account. Compared to MOVES we note that iBEAM is limited in its analysis to passenger cars and light trucks. Furthermore, we employ simplified vehicle activity data and rely on compliance with vehicle emissions standards.

For greenhouse gas emissions assessments, we rely on data from the GREET model developed by Argonne National Laboratory which is the gold standard for U.S. based life cycle analysis and contains the most up to date information on corn ethanol production. We also utilize the Biograce Model which is a European life cycle model that evaluates European fuel pathways under the Renewable Energy Directive (RED). Current Japanese modeling efforts are closely aligned with the EU RED methodology.

2 Structure of the iBEAM Emissions Model

This section provides an overview of the iBEAM structure. Each module will be further explained in the following sections.

The iBEAM model consists of a vehicle characterization module which is combined with an emission factor assessment for both gasoline and ethanol to derive total emissions adjustments from ethanol blended gasoline. Separately, the impact from the production of E10 and E20 fuels on refinery revenue is being assessed.

The vehicle characterization includes a projection of annual gasoline passenger car population multiplied by the distance travelled annually by each car to derive the total driven passenger distance (total kilometers) in each city. The passenger car population is a) also corrected for projected electric vehicle share and b) broken out by annual new car additions including replacement of retired vehicles.

The emissions factors for both gasoline and ethanol are assessed in two different ways:

- Emissions Factors for Gasoline from Complex Model. In this case we ran the US EPA Complex Model with country specific gasoline samples to derive emissions factors for gasoline.
- Emissions Factors for Ethanol from Complex Model. A base gasoline was established for each city that met the properties of the gasoline samples followed by a modeled adjustment of the gasoline blend stocks from ethanol blending.
- Emissions Factors for Gasoline from past and future emissions standards. The past, current, and future emissions standards governing each city was surveyed for each city. The standards specify the emissions limits set for gasoline passenger vehicles for the applicable test protocols.
- Emissions Factors for Ethanol from published vehicle emissions studies. We surveyed the literature for substantially all major gasoline-ethanol vehicle emissions studies (for E10 and E20) and summarized the expected impact from ethanol on combustion emissions.

Since emissions factors for gasoline and ethanol are only representative for the underlying vehicle fleet and control technology a correction of emissions factors by vehicle age was introduced. Finally, for hydrocarbon emissions the effects of altitude and reid vapor pressure on evaporative emissions were added as well as an explicit representation of refueling losses, permeation, spillage, and onboard refueling vapor recovery (ORVR) technologies.

In most scenarios the blending of E10, E20 will enable refineries to produce more gasoline volume which will overall increase revenue. That revenue addition is compared against the need to add hydrogen production capacity to offset reduced production from the reforming unit within the refinery. The figure below provides a representation of the model structure. Appendix B provides a Quickstart to the iBEAM Excel spreadsheet.

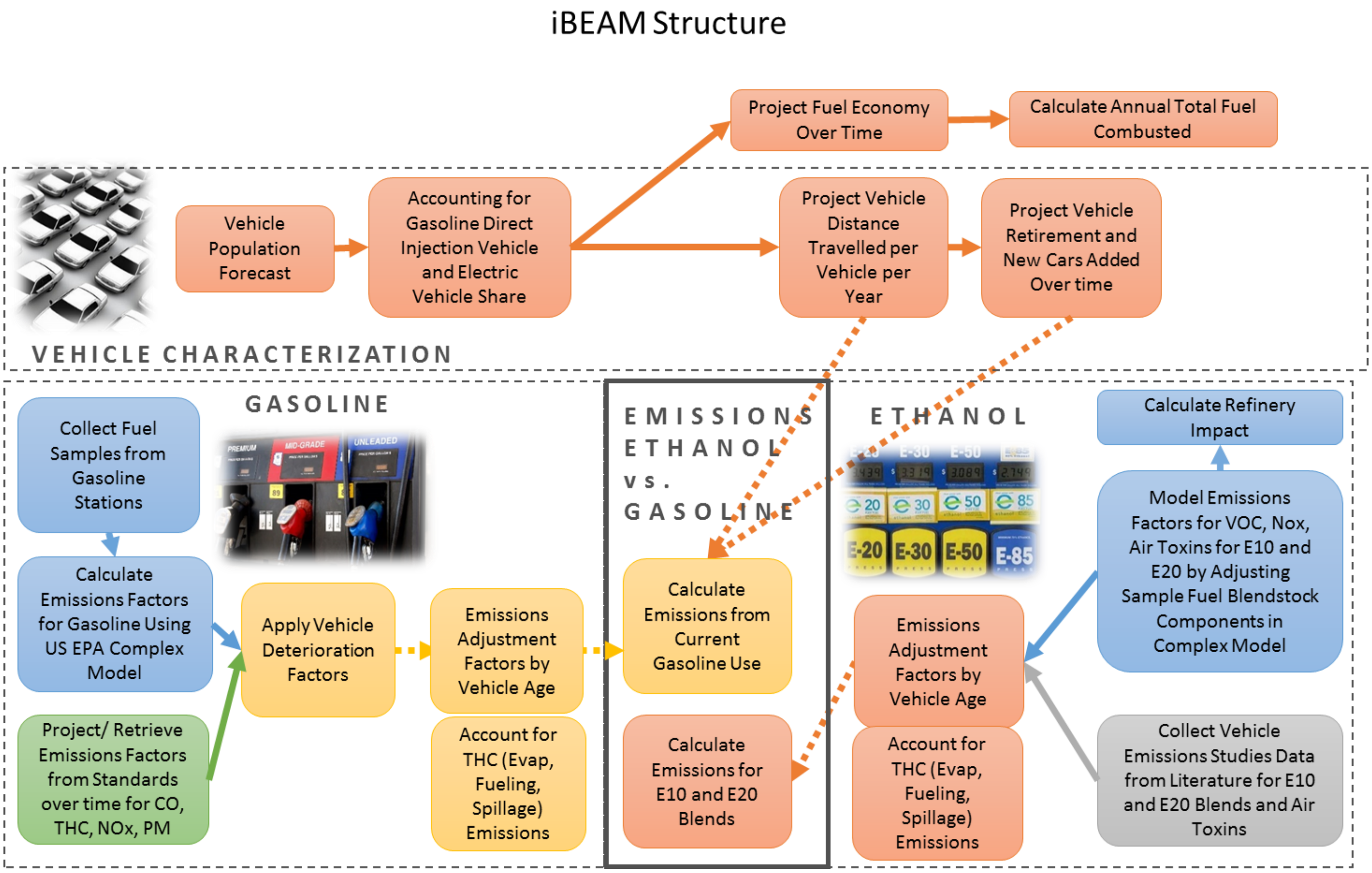


Figure 1: iBEAM Flow Diagram

3 Vehicle Characterization

3.1 Vehicle Population, Distance Travelled, and Fuel Economy

The vehicle characterization includes a projection of the annual gasoline passenger car population multiplied by the distance travelled by each car to derive the total driven passenger distance (total kilometers) in each city. This number is relevant since it can be multiplied by the emissions factors which are assessed in grams of pollutant per distance (e.g. kilometer) traveled to derive the total emissions from gasoline vehicles in a year.

The passenger car population in iBEAM is assessed for each city according to two separate methods: a) by extrapolating historic data on vehicle saturation levels (customarily stated in vehicles per 1000 people multiplied by projected population levels for each city and b) by reviewing existing vehicle studies for the respective country and city. For example, the figure below shows the extrapolation of vehicle data for Beijing. This data was then triangulated with published studies including an announcement that Beijing will limit vehicle sales to 6.3 million vehicles by to end of 2020.

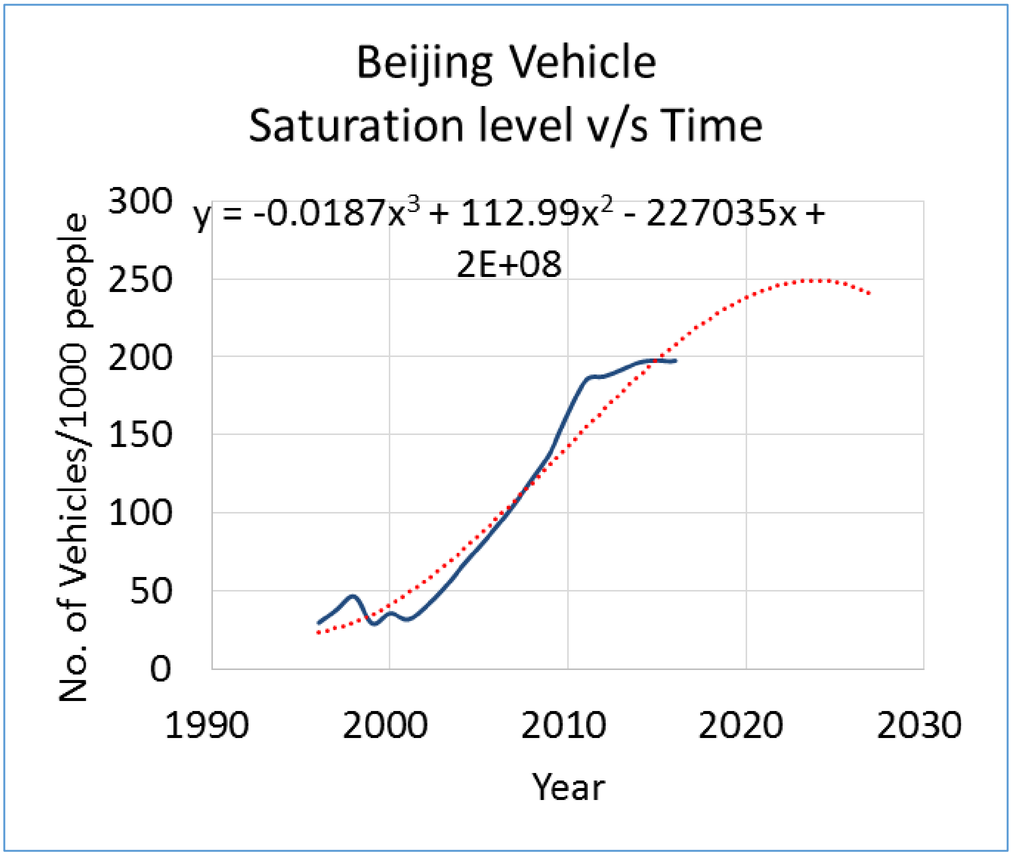


Figure 2: Example of Vehicle Population Estimation

Based on this approach we derived the vehicle populations for our cities shown in the graph below.

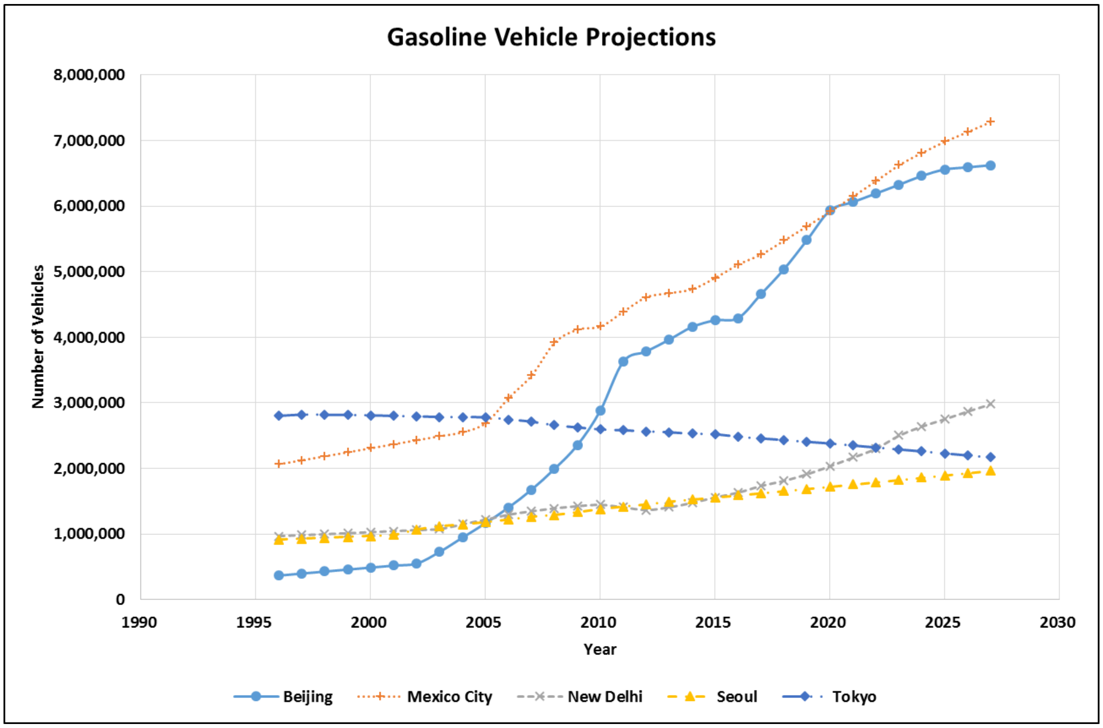


Figure 3: Summary of Gasoline Vehicle Projections by City

The tables below detail the citations used in iBEAM to characterize passenger car population and vehicle distance travelled.

Table 1: Sources for Gasoline Car Population

City	**Citation**	**Notes**
Beijing	• National Bureau of Statistics of China http://www.stats.gov.cn/english/statisticaldata/AnnualData/	The data has been obtained by accessing the data sheet of every year and populating it into the excel file. **China has banned all Diesel vehicles from the year 2000, thus all vehicle data is Gasoline only.**
Mexico City	• National Statistical and Geographic Information System "INEGI," [Online]. Available: http://www.inegi.org.mx/	Filters for Mexico City Metropolitan Area are applied, and the values for Passenger Vehicles are taken. The number of Diesel vehicles make up less than 0.1% of the data shown, thus all data provided are taken as Gasoline vehicles.
New Delhi	• "Economic survey of Delhi," [Online]. Available: http://delhi.gov.in/wps/wcm/connect/DoI	First citation gives the total population of passenger vehicles in Delhi. Second citation's appendix gives the

	T_Planning/planning/our+services1/economic+survey+of+delhi . [Accessed 22 June 2017]. - S. G. Rahul Goel, "Evolution of on-road vehicle exhaust emissions in Delhi," *Atmospheric Environment*, vol. 105, pp. 78-90, March 2015.	split and projection between the gasoline and diesel vehicles.
Seoul	- "Number of Registered Motor Vehicles and Emission Quantity," 2013. [Online]. Available: http://eng.me.go.kr/eng/web/index.do?menuId=254 . [Accessed 24 July 2017] . - KAMA, 2016. [Online]. Available: http://stat.molit.go.kr/portal/cate/engStatListPopup.do. [Accessed 24 July 2017].	The first citation gives the data of number of vehicles in South Korea. The second citation gives the data of number of gasoline vehicles in Seoul, for few years. **The same percentage has been applied throughout the study as Seoul has incremental increase in vehicle population over the years.**
Tokyo	- http://www.toukei.metro.tokyo.jp/homepage/ENGLISH.htm - "Diesels may return to Japan roads," NY Times, 3 March 2006. [Online]. Available: http://www.nytimes.com/2006/03/03/business/worldbusiness/diesels-may-return-to-japan-roads.html . [Accessed 24 July 2017].	The first citation gives the data of number of vehicles in Tokyo from the statistical year book. The second citation gives the data of number of gasoline vehicles in Japan as a split with Diesel, for few years. **5% has been applied as the diesel share throughout the study as Tokyo has little changes in vehicle population over the years.**

The vehicle distance travelled by each car differs by city based on several factors including the geographic expansion of the city boundaries and the development of public transportation systems. For example, Guerra shows that the average vehicle distance travelled for Mexico City has increased over the past years, and that this trend will likely continue with outward urban sprawl. [6] . Conversely, for Seoul Myung-JinJun et. all, argue that with the "greenbelt and newtown development" in Seoul, commuting costs and travel distances would be significantly reduced. The table below lists the citations used in iBEAM for vehicle distance travelled per car followed by a summary graph.

Table 2: Sources for Vehicle Distance Travelled

City	**Citation**	**Notes**
Beijing	• He, "Oil consumption and CO2 emissions in China's road transport: Current status, future trends, and policy implications," *Enrgy policy*, vol. 33, no. 12, pp. 1499-1507, August 2015. • Huo, "Projection of Chinese motor vehicle growth, oil demand, and CO2 emissions through 2050," *Transportation research record*, no. 2038, pp. 69-77, 2007	The data has been obtained by the two research papers. Values have been projected for future years. The missing middle data has been interpolated
Mexico City	• C. S.-P. Carlos Chavez-Baeza, "Sustainable passenger road transport scenarios to reduce fuel consumption, air pollutants and GHG (greenhouse gas) emissions in the Mexico City Metropolitan Area," *Energy*, vol. 66, pp. 624-634, March 2014. • http://journals.sagepub.com/doi/pdf/10.1177/0739456X14545170 *	The data has been obtained from the first research paper. The second paper argues for an ever increasing VDT in Mexico City, owing to its geographic expansion.
New Delhi	• S. G. Rahul Goel, "Evolution of on-road vehicle exhaust emissions in Delhi," *Atmospheric Environment*, vol. 105, pp. 78-90, March 2015.	Data has been obtained from the appendix of the citation.
Seoul	• http://kosis.kr/eng/statisticsList/statisticsList_01List.jsp#SubCont • http://www.sciencedirect.com/science/article/pii/S0264275101000075 **	Data from the citation gives the annual VDT for the years 2011-16. The second citation gives the city VKT trend for the remaining years.
Tokyo	• http://www.toukei.metro.tokyo.jp/homepage/ENGLISH.htm	Citation gives the statistical year book of Tokyo. VDT is in terms of annual kilometers driven. Data has been calculated per vehicle from vehicle population data.

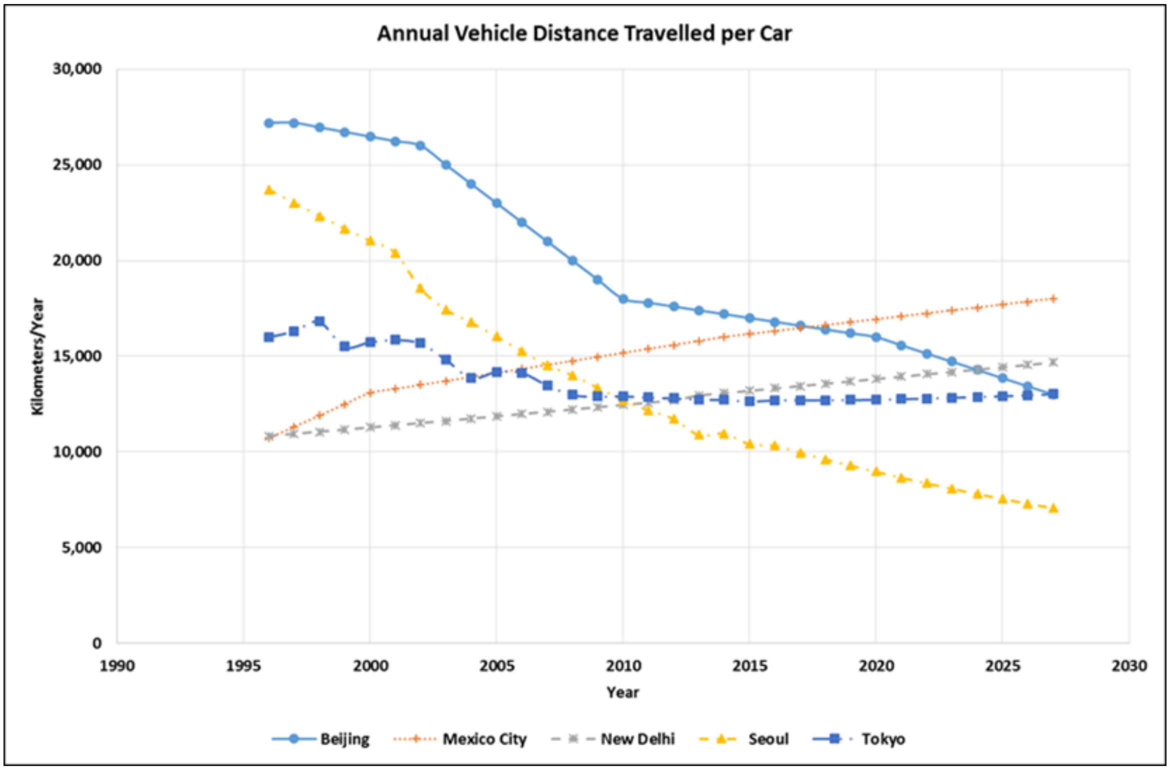


Figure 4: Summary of Annual Vehicle Distance Travelled by City

Fuel economy factors were developed for each of the cities. These factors are necessary for the fuelage, spillage, and permeation emissions calculations discussed in the respective section of this report. The table below lists the citations for the employed fuel economy values in iBEAM followed by a summary graph.

Table 3: Sources for Fuel Economy

City	**Citation**	**Notes**
Beijing	- He, "Oil consumption and CO2 emissions in China's road transport: Current status, future trends, and policy implications," *Enrgy policy*, vol. 33, no. 12, pp. 1499-1507, August 2015. - Han Haoa, "Comparison of policies on vehicle ownership and use between Beijing and Shanghai and their impacts on fuel consumption by passenger vehicles," *Energy policy*, vol. 39, no. 2, pp. 1016-1021, February 2011	The data has been obtained by the two research papers. Values have been projected for future years. The missing middle data has been interpolated.

Mexico City	• http://dof.gob.mx/nota_detalle.php?codigo=2091196&fecha=07/09/2005. • C. S.-P. Carlos Chávez-Baeza, "Fuel economy of new passenger cars in Mexico: Trends from 1988 to 2008 and prospects," *Energy Policy*, vol. 39, no. 12, pp. 8153-8162, December 2011.	The data has been obtained by the two research papers. Values have been projected for future years. The missing middle data has been interpolated.
New Delhi	• M. M. a. J. S. Stephane de la Rue du Can, "India Energy Outlook: End Use Demand in India to 2020," *ERNEST ORLANDO LAWRENCE BERKELEY NATIONAL LABORATORY*, January 2009.	Data has been obtained from the citation. Missing data has been interpolated.
Seoul	• "South Korea: Light-duty: Fuel Economy and GHG," 26 February 2016. [Online]. Available: http://transportpolicy.net/index.php?title=South_Korea:_Light-duty:_Fuel_Economy_and_GHG . [Accessed 24 Jul4 2017].	Seoul has defined a series of targets for manufacturers to achieve over the next few years.
Tokyo	• "Japan: Light-duty: Fuel Economy," icct and DieselNet, 3 January 2017. [Online]. Available: http://transportpolicy.net/index.php?title=Japan:_Light-duty:_Fuel_Economy . [Accessed 25 July 2017].	Tokyo has defined a series of targets for manufacturers to achieve over the next few years.

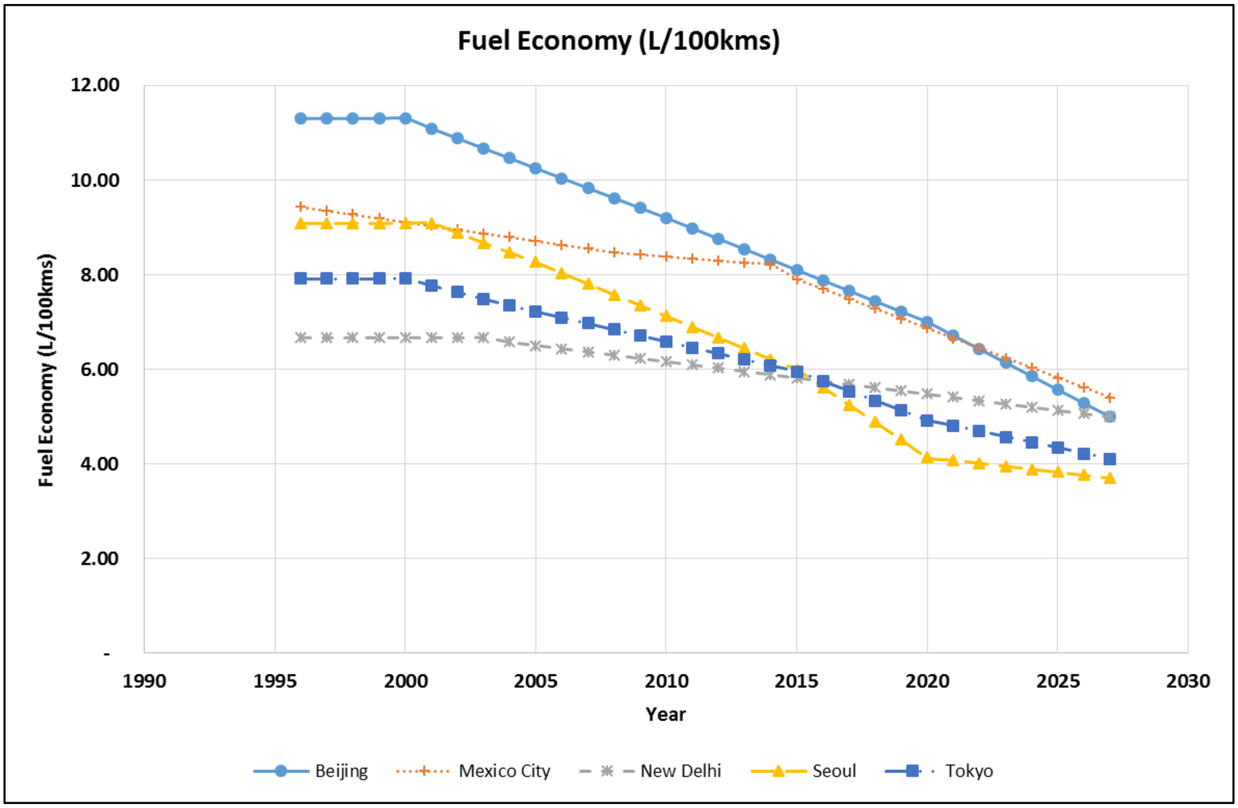


Figure 5: Summary of Fuel Economy by City

3.2 Electric Vehicle Share

In iBEAM we correct the vehicle population for the projected adoption of electric vehicles. Increased interest in EV power trains has been widely discussed in recent articles including a recent announcement by Volvo to manufacture solely battery-only and battery-hybrid vehicles by 2019 [7]. Estimates regarding the future adoption rate of this technology vary widely. A recent study by ReThinkX asserts that purely by economic factors, 95% of vehicle miles driven will be by electric vehicles by the year 2030 [8]. By contrast, a comment by Reg Modlin, former Director of Regulatory Affairs at Fiat Chrysler Automotive and a present Senior Advisor to the Ag-Auto-Ethanol Working Group, speaks more cautionary about the projected EV influence. He shows that recent aggressive electrification announcements by Volvo and Daimler still include provisions that internal combustion engines are included in mild-hybrid (Start/Stop), hybrid and plug-in hybrid systems [9].

Here are some regional positions from our areas of interest.

New Delhi, India
India has taken an aggressive stance to manufacture and sell only electric vehicles by the end of 2030. The energy minister has stated the intention to facilitate growth of the EV effort by subsidizing the cost of EVs for a couple of years until they become economically viable. With their target of 6-7 million EVs by the end of 2020, New Delhi could be a considerable adopter of EV technologies [10].

Beijing, China
China recently introduced a new vehicle energy score with aggressive targets of 10 percent of low or zero emissions vehicle sales per auto manufacturer starting in 2019, rising to 12 percent in 2020. [11] [12, 13].

Tokyo, Japan
A recent study by Nissan showed that Japan has more EV charging stations than gas fueling stations. Japan has been ahead of the curve in their interest in EVs, and started about a decade ago with infrastructure build out. Japan has set up subsides for charging station installations, provided tax incentives, and permits lanes used by buses and taxis to be used by EVs. Japan is likely a strong adopter of EV technologies [14, 15, 16].

Seoul, South Korea
South Korea offers a subsidy of up to 26 million won (~$23,000) per vehicle for the purchase of EVs. This provides an edge for small compact EVs to enter the market much sooner, which is the major target for South Korea in easing up congestion. Sale of EVs in Korea doubled in 2016 from 2015. The nation is setting up targets for EV companies to meet charging driving range targets [17, 18].

Mexico City, Mexico
Mexico has not made any significant efforts with its development of an electric vehicle market. However, there have been some talks about collaborations within companies to start a locally-made electric car company and Mexico is certainly a leader in vehicle manufacturing [19]. Nevertheless we expect Mexico to be a slower adopter of EV technologies.

We searched the literature for global EV adoption rate projections. Whitmore developed a global EV adoption model which projects EV stock for three cases reflective of a slower, moderate, and strong policy scenario [20]. The study shows that annual EV vehicle sales will account for between 20% to 60% by the year 2030 converting to 7% and 22% of total vehicle stock depending on the policy scenario. A Roland Berger report cites annual new vehicle sales (Figure 21 of that report) of EVs by 2030 of 19% (3% Battery Hybrid plus 3% Plug-in Electric Vehicle plus 1% Full Hybrid and 11% Mild Hybrid) which would correspond more closely with the slower adoption scenario by Whitmore [21]. In the Whitmore article we read the graphs for 2027 and derive stock shares of 4%, 7%, and 11% for the slower, moderate, and strong policy, respectively. We believe that these adoption rates may be realistic and we have therefore incorporated these rates into our modeling.

3.3 Vehicle Retirement

We consider vehicle retirement in our model. The retirement of vehicles increases the amount of new vehicles brought into the vehicle pool which reduces overall emissions due to their compliance with the newest standards.

We adopted the retirement matrix in Argonne's Vision model [22]. The Vision model lists year over year survival factors which represent the fraction of cars on the road for each model year compared to the subsequent year. The adopted retirement matrix from Vision in iBEAM calculates the number of vehicles for each model year in a given calendar year. New vehicle purchases are determined from the projection of on road vehicles minus the calculation of surviving vehicles from prior years. The surviving vehicles in each year is determined from the year over year survival rate. Surviving cars are calculated for subsequent years. The iBEAM model tracks vehicle introductions since 1996.

4 Emissions Factors for Gasoline and Ethanol Based on the Complex Model

4.1 Gasoline Sampling

To get a baseline for blending, three gasoline samples were taken in each city and their compositions analyzed to determine what gasoline properties were prevalent. The samples were taken and analyzed by local Intertek Laboratories affiliates. Three samples were collected in each city, generally from different fuel providers and random geographic locations. The table below summarizes averages for some of the major properties from sampling gasoline in each city.

Table 4: Properties of Sampled Gasolines

		Beijing	Seoul	Tokyo	New Delhi	Mexico City
RON		88.2				88.6
MON						80.6
Specific Gravity		0.679				0.721
Sulfur	mg/kg	6.3	5.7	6.7	16.7	
RVP	psi	5.84	8.54	9.43	7.92	7.63
RVP	kPa	40.3	58.9	65.0	51.7	52.6
Benzene	vol%	0.62	0.46	0.59	1.17	0.46
Aromatics	vol%	25.2	10.4	22.5	31.6	17.8
Olefins	vol%	12.3	13.0	15.1	13.8	6.0
Oxygenate						
MTBE	vol%	6.98	0	0		11.13
ETBE	vol%	0	0	6.42	0	0.00
MTBE	wt%				1.97	

4.2 Methodology for Estimating Impact of Blending Ethanol vs. MTBE and ETBE

While gasoline sampling provided many of the major gasoline properties it was 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 get around this limitation and show the change in gasoline properties from ethanol blending, a base gasoline was first established for each city that met the properties of the gasoline samples shown in Table x-1. Next the recipe was adjusted by blending ethanol while keeping the gasoline octane and RVP at the same values as in the base gasoline.

The impact of ethanol blending in gasoline used in each city was estimated by looking at the change in gasoline properties and change in toxics emissions from gasoline use. The EPA Complex Model was used to estimate emissions of exhaust benzene, acetaldehyde, formaldehyde, 1,3 butadiene, and polycyclics as well as nonexhaust benzene emissions from using each gasoline in a vehicle. Emissions are estimated based on the following gasoline composition parameters: vol% benzene, vol% aromatics, vol% olefins, vol% evaporated at 200 °F (E200), vol% evaporated at 300 °F (E300), weight parts per million (ppm) sulfur, RVP as psi, wt% oxygen, and vol% and type of oxygenate blended.

The EPA Complex Model was developed over twenty years ago and is still used by refiners today for compliance purposes and it can be used to estimate emissions from gasoline use in older vehicles. For the purpose of this study the relative change in emissions from one gasoline sample to another was used as an indicator of directional change in emissions from blending different oxygenates.

The first step in this analysis was to establish a gasoline recipe for each city from gasoline blend stocks produced from a hypothetical refinery having the refining capacity representative of the country in which the city was located. Next the gasoline recipe was adjusted by adding ethanol and replacing MTBE or ETBE if these oxygenates were used. Ethanol addition was at either 10 or 20 vol% in the final gasoline. Gasoline blends were also prepared with no oxygenate and with the oxygenate type and level reported in the city gasoline samples. If the city gasoline samples reported MTBE use, a blend was prepared with the same volume of ETBE and vice versa.

To meet gasoline octane and RVP specifications, the severity of the catalytic reforming unit was adjusted and butane and pentanes removed or butane added as needed. Feed to the catalytic reforming unit was allowed to bypass the unit to meet gasoline octane and maximize gasoline production. Reformate benzene and aromatics levels, volume and hydrogen yield changed with reforming unit severity. Gasoline olefins and distillation percent evaporated at 200 °F and 300 °F (E200 and E300) changed as a result of blending oxygenates and changing reforming unit operation. Gasoline blending, including changes in reforming unit yields, was done using a linear programming model. The properties for each gasoline produced for each city from the blending recipe were put into the EPA Complex Model to estimate toxics emissions. The relative change in emissions from the base gasoline were reported.

4.3 Gasoline Blend Specifications

Gasoline blending constraints were set by country level gasoline specifications shown in Table x-2. In many countries there is a range of RONs specified. For this study, the middle RON was chosen as the specification for blending. Mexico uses (R+M)/2 for its specifications and has a specification of 87 (R+M)/2 for regular and 91 (R+M)/2 for premium. It was decided to use the 87 (R+M)/2 as the gasoline octane specification for Mexico in this study.

Most countries had an upper RVP specification for gasoline. Japan had a range, so it was decided to use 60 kPa as the upper limit, which is consistent with Korean gasoline. Japan did not set a limit on aromatics or olefins. It was decided to use 40 vol% as the upper limit on aromatics and 25 vol% as the upper limit on olefins for Japan.

Table 5: Gasoline Blend Specifications

		Beijing	Seoul	Tokyo	New Delhi	Mexico City
		China	South Korea	Japan	India	Mexico
RON	min	92.0	94.0	91.6	91.0	
MON	min				81.0	
(R+M)/2	min					87
RVP	psi max	9.43	8.70	8.70	8.70	7.80
RVP	kPa max	65	60	60	60	54
Benzene	vol% max	1	0.7	1	1	1
Aromatics	vol% max	40	24	40	35	25
Olefins	vol% max	24	18	25	21	10
Sulfur	ppm max	10	10	10	10	30
Oxygen	wt% max	2.7	2.3	1.3	2.7	2.7
MTBE	vol% max			7.0		

4.4 Gasoline Blending Results and Emissions Factor Results

Model results for each city with no oxygenate, with MTBE or ETBE at the average level in the gasoline sampled for each city, and with 10 and 20 vol% ethanol are shown in the following tables for each city. These results summarize the impact on catalytic reforming unit severity, change in gasoline volume and catalytic reforming unit hydrogen production from the base. The relative amount of gasoline blendstock used for each gasoline blend using 100 as the volume of gasoline in the base case for each city are shown. Gasoline properties are shown as are the relative change in toxics emissions relative to the base gasoline for each city.

Gasoline meets the RVP spec for each country. Gasoline octanes are the same for each blending case with the exception when blending 20 vol% ethanol. For this case, the RON was allowed to go to 95, which is a potential gasoline specification that will enable greater use of higher efficiency gasoline engines.

Table 6: Complex Model Emissions Results Beijing

		Beijing		
		MTBE	Ethanol-10	Ethanol-20
CHANGE FROM BASE		BASE-Beijing		
Gasoline Volume - Relative	BPD	100.0	104.1	119.2
Hydrogen from Catalytic Reformer - Relative	MM SCF/day	10.4	5.4	2.2
Gasoline Volume Change from Base		0.0%	4.1%	19.2%
Hydrogen Volume Change from Base		0.0%	-47.8%	-79.2%
Catalytic Reforming Unit Octane (Severity)	RON	98.5	88.0	88.0
OXYGENATE MIX				
MTBE	vol%	6.98%	0.0%	0.0%
ETBE	vol%	0.0%	0.0%	0.0%
ETHANOL	vol%	0.0%	10.0%	20.0%
TAME	vol%	0.0%	0.0%	0.0%
GASOLINE PROPERTIES				
RON		91.9	92.0	94.9
MON		83.0	82.0	81.8
(R+M)/2		87.5	87.0	88.4
Specific Gravity		0.7582	0.7499	0.7447
Oxygen	wt%	1.2	3.7	7.4
Sulfur	ppm	6.9	6.6	5.9
RVP	psi	9.4	9.4	9.4
E200	vol%	47.2	52.8	60.8
E300	vol%	79.7	79.3	83.6
Aromatics	vol%	27.1	26.2	23.3
Olefins	vol%	13.2	12.8	11.4
Benzene	vol%	0.66	0.64	0.57
GASOLINE BLENDSTOCKS				
Butane	vol%	3.81	2.30	2.13
MTBE	vol%	6.98	0.00	0.00
ETBE	vol%	0.00	0.00	0.00
Ethanol	vol%	0.00	10.00	20.00
Light Straight Run Naphtha	vol%	9.83	9.44	8.24
Penex	vol%	0.00	0.00	0.00
Pen_DIH	vol%	0.00	0.00	0.00
Pen_PSA	vol%	0.00	0.00	0.00
Light Hydrocracked Naphtha	vol%	6.43	6.18	5.40
Light Coker Naphtha	vol%	0.00	0.00	0.00
Alkylate	vol%	2.16	2.07	1.81
Natural Gasoline	vol%	0.00	0.00	0.00
Reformer Feed	vol%	0.00	4.61	14.09
Reformate	vol%	20.10	16.68	5.81
FCC_Naphtha	vol%	50.70	48.72	42.53
Gasoline Volume	vol%	100.00	100.00	100.00
EMISSIONS - EPA COMPLEX MODEL				
VOC				
Exhaust	mg/mile	840.93	818.61	768.40
Non-exhaust	mg/mile	722.87	722.87	722.87
Total VOC	mg/mile	1563.80	1541.48	1491.27
NOx	mg/mile	1197.12	1194.28	1176.65
TOXICS				
Exhaust				
Benzene	mg/mile	31.43	26.83	21.18
Acetaldehyde	mg/mile	4.22	11.14	27.24
Formaldehyde	mg/mile	10.28	9.88	9.88
Butadiene	mg/mile	10.31	9.07	7.00
Polycyclics	mg/mile	2.82	2.75	2.58
Subtotal	mg/mile	59.07	59.68	67.89
Non-Ehxaust				
Benzene	mg/mile	3.02	3.11	2.77
Total Toxics	mg/mile	62.09	62.79	70.65

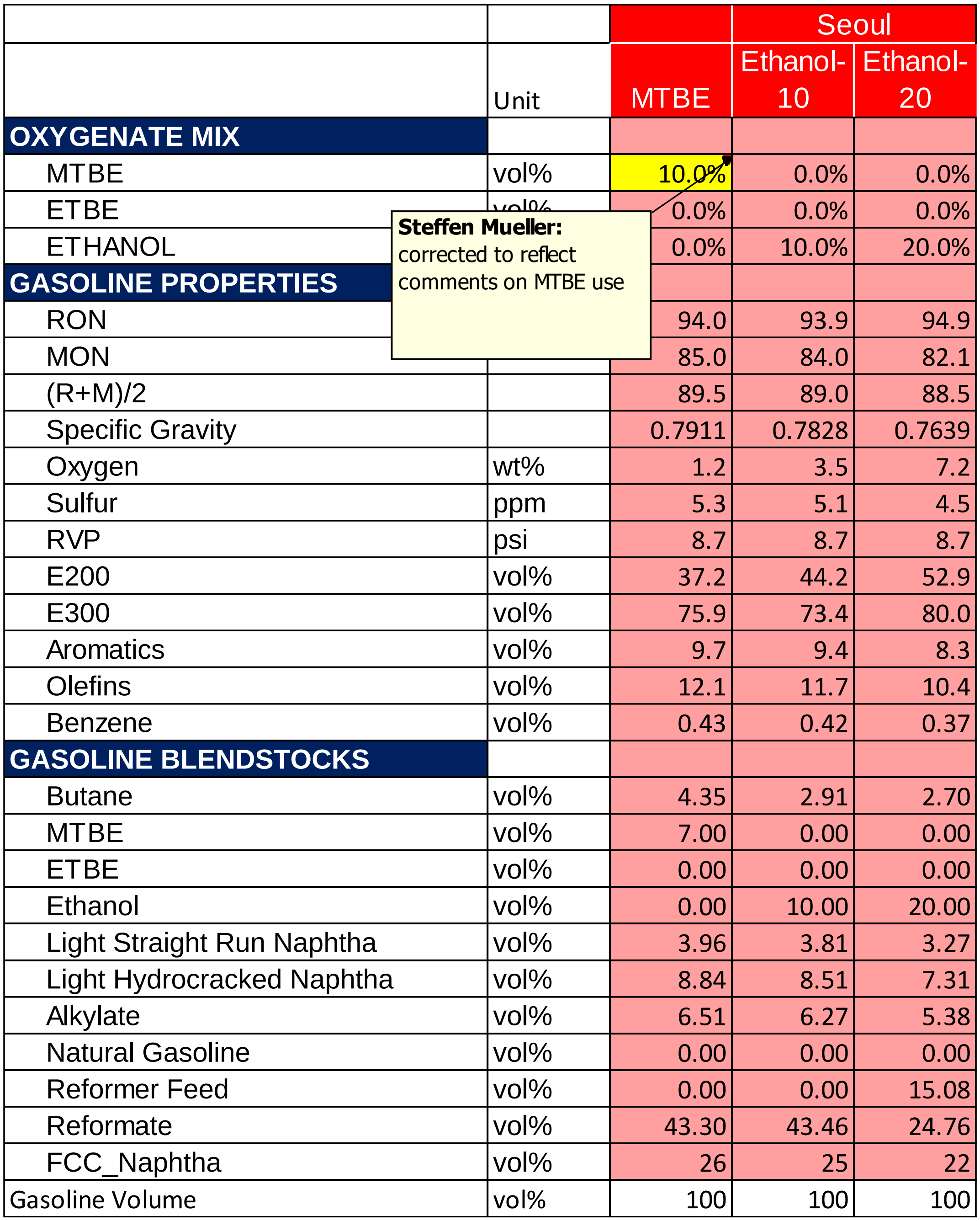
Table 7: Complex Model Results Mexico City

		MTBE	Ethanol-10	Ethanol-20
CHANGE FROM BASE		BASE-Mexico City		
Gasoline Volume - Relative	BPD	100.0	100.3	112.3
Hydrogen from Catalytic Reformer - Relative	MM SCF/	51.8	43.0	28.4
Gasoline Volume Change from Base		0.0%	0.3%	12.3%
Hydrogen Volume Change from Base		0.0%	-17.0%	-45.2%
Catalytic Reforming Unit Octane (Severity)	RON	101.0	101.0	101.0
OXYGENATE MIX				
MTBE	vol%	11.13%	0.0%	0.0%
ETBE	vol%	0.0%	0.0%	0.0%
ETHANOL	vol%	0.0%	10.0%	20.0%
TAME	vol%	0.0%	0.0%	0.0%
GASOLINE PROPERTIES				
RON		91.0	91.5	95.0
MON		83.1	82.6	82.8
(R+M)/2		87.1	87.1	88.9
Specific Gravity		0.7671	0.7656	0.7609
Oxygen	wt%	2.0	3.6	7.3
Sulfur	ppm	11.3	11.4	10.2
RVP	psi	7.8	7.8	7.8
E200	vol%	38.2	43.1	52.0
E300	vol%	82.5	81.7	84.1
Aromatics	vol%	20.0	20.3	18.0
Olefins	vol%	6.7	6.8	6.0
Benzene	vol%	0.52	0.53	0.47
GASOLINE BLENDSTOCKS				
Butane	vol%	3.53	2.26	2.21
MTBE	vol%	11.13	0.00	0.00
ETBE	vol%	0.00	0.00	0.00
Ethanol	vol%	0.00	10.00	20.00
Light Straight Run Naphtha	vol%	0.37	2.15	0.11
Penex	vol%	0.00	0.00	0.00
Pen_DIH	vol%	0.00	0.00	0.00
Pen_PSA	vol%	0.00	0.00	0.00
Light Hydrocracked Naphtha	vol%	0.00	0.00	0.00
Light Coker Naphtha	vol%	0.00	0.00	0.00
Alkylate	vol%	17.95	17.90	15.99
Natural Gasoline	vol%	0.00	0.00	0.00
Reformer Feed	vol%	14.32	18.47	22.70
Reformate	vol%	19.73	16.34	9.62
FCC_Naphtha	vol%	32.97	32.88	29.36
Gasoline Volume	vol%	100.00	100.00	100.00
EMISSIONS - EPA COMPLEX MODEL				
VOC				
Exhaust	mg/mile	799.46	777.10	731.16
Non-exhaust	mg/mile	405.79	404.37	405.79
Total VOC	mg/mile	1205.26	1181.47	1136.95
NOx	mg/mile	1124.08	1128.92	1120.49
TOXICS				
Exhaust				
Benzene	mg/mile	26.60	24.24	19.17
Acetaldehyde	mg/mile	4.02	10.67	26.07
Formaldehyde	mg/mile	12.16	11.15	11.22
Butadiene	mg/mile	8.45	7.82	6.30
Polycyclics	mg/mile	2.68	2.61	2.45
Subtotal	mg/mile	53.91	56.49	65.22
Non-Ehxaust				
Benzene	mg/mile	1.56	1.71	1.52
Total Toxics	mg/mile	55.47	58.20	66.74

Table 8: Complex Model Results New Delhi

		New Delhi		
		MTBE	Ethanol-10	Ethanol-20
CHANGE FROM BASE		BASE-New Delhi		
Gasoline Volume - Relative	BPD	100.0	120.9	144.1
Hydrogen from Catalytic Reformer - Relative	MM SCF/day	5.4	0.0	0.0
Gasoline Volume Change from Base		0.0%	20.9%	44.1%
Hydrogen Volume Change from Base		0.0%	-99.9%	-99.9%
Catalytic Reforming Unit Octane (Severity)	RON	101.0	88.0	88.0
OXYGENATE MIX				
MTBE	vol%	1.95%	0.0%	0.0%
ETBE	vol%	0.0%	0.0%	0.0%
ETHANOL	vol%	0.0%	10.0%	20.0%
TAME	vol%	0.0%	0.0%	0.0%
GASOLINE PROPERTIES				
RON		91.0	91.1	95.5
MON		83.3	82.0	83.2
(R+M)/2		87.1	86.5	89.3
Specific Gravity		0.7423	0.7283	0.7321
Oxygen	wt%	0.4	3.8	7.5
Sulfur	ppm	17.0	15.6	13.9
RVP	psi	8.7	8.7	8.7
E200	vol%	47.6	57.0	67.0
E300	vol%	81.6	85.1	85.9
Aromatics	vol%	32.2	29.6	26.3
Olefins	vol%	14.1	12.9	11.5
Benzene	vol%	1.19	1.09	0.97
GASOLINE BLENDSTOCKS				
Butane	vol%	2.56	0.49	0.03
MTBE	vol%	1.95	0.00	0.00
ETBE	vol%	0.00	0.00	0.00
Ethanol	vol%	0.00	10.00	20.00
Light Straight Run Naphtha	vol%	1.82	7.06	5.92
Penex	vol%	0.00	0.00	0.00
Pen_DIH	vol%	0.00	0.00	0.00
Pen_PSA	vol%	0.00	0.00	0.00
Light Hydrocracked Naphtha	vol%	8.14	6.73	5.64
Light Coker Naphtha	vol%	0.00	0.00	0.00
Alkylate	vol%	16.70	13.81	11.59
Natural Gasoline	vol%	0.00	3.31	7.64
Reformer Feed	vol%	0.00	8.39	7.04
Reformate	vol%	8.11	0.01	0.01
FCC_Naphtha	vol%	60.73	50.21	42.13
Gasoline Volume	vol%	100.00	100.00	100.00
EMISSIONS - EPA COMPLEX MODEL				
VOC				
Exhaust	mg/mile	826.15	771.75	748.50
Non-exhaust	mg/mile	560.77	560.77	560.77
Total VOC	mg/mile	1386.92	1332.52	1309.26
NOx	mg/mile	1219.21	1208.05	1194.73
TOXICS				
Exhaust				
Benzene	mg/mile	41.34	32.40	24.53
Acetaldehyde	mg/mile	4.10	10.37	26.60
Formaldehyde	mg/mile	9.21	9.07	9.43
Butadiene	mg/mile	10.50	8.14	6.44
Polycyclics	mg/mile	2.77	2.59	2.51
Subtotal	mg/mile	67.92	62.57	69.51
Non-Ehxaust				
Benzene	mg/mile	4.78	4.46	3.97
Total Toxics	mg/mile	72.71	67.03	73.47

Table 9: Complex Model Emissions Factor Results – Seoul



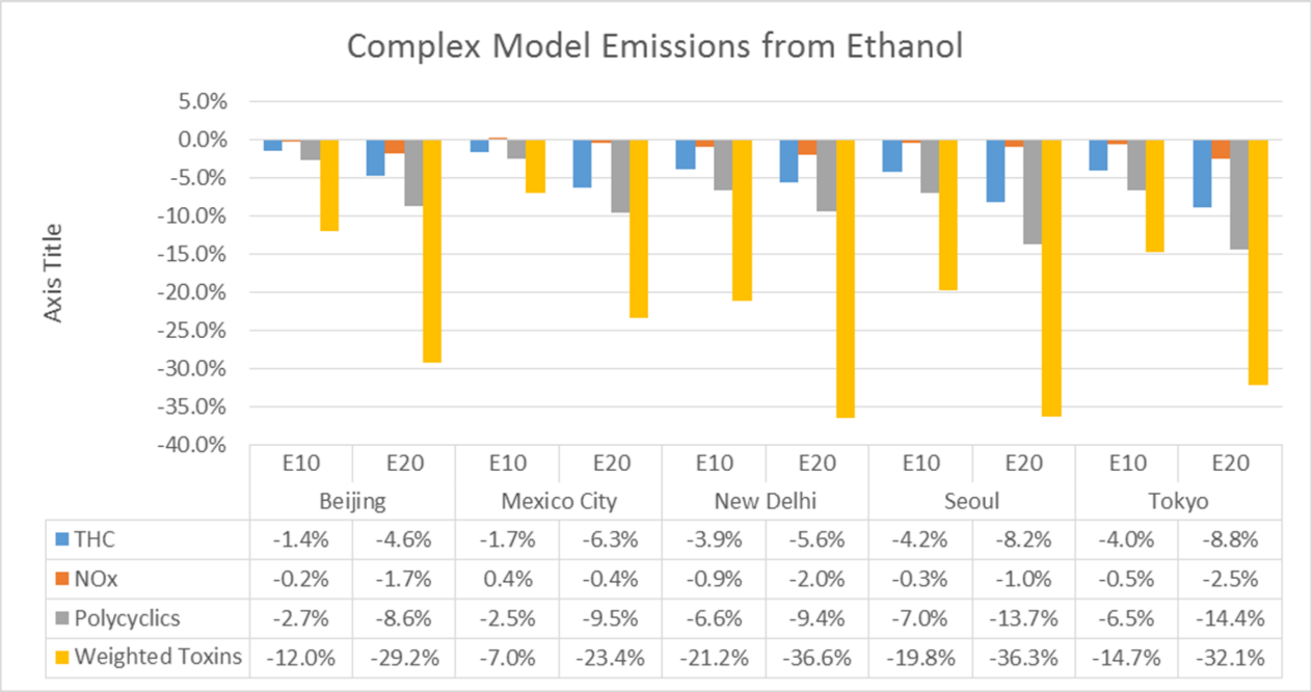
		Seoul		
	Unit	MTBE	Ethanol-10	Ethanol-20
OXYGENATE MIX				
MTBE	vol%	10.0%	0.0%	0.0%
ETBE	vol%	0.0%	0.0%	0.0%
ETHANOL		0.0%	10.0%	20.0%
GASOLINE PROPERTIES				
RON		94.0	93.9	94.9
MON		85.0	84.0	82.1
(R+M)/2		89.5	89.0	88.5
Specific Gravity		0.7911	0.7828	0.7639
Oxygen	wt%	1.2	3.5	7.2
Sulfur	ppm	5.3	5.1	4.5
RVP	psi	8.7	8.7	8.7
E200	vol%	37.2	44.2	52.9
E300	vol%	75.9	73.4	80.0
Aromatics	vol%	9.7	9.4	8.3
Olefins	vol%	12.1	11.7	10.4
Benzene	vol%	0.43	0.42	0.37
GASOLINE BLENDSTOCKS				
Butane	vol%	4.35	2.91	2.70
MTBE	vol%	7.00	0.00	0.00
ETBE	vol%	0.00	0.00	0.00
Ethanol	vol%	0.00	10.00	20.00
Light Straight Run Naphtha	vol%	3.96	3.81	3.27
Light Hydrocracked Naphtha	vol%	8.84	8.51	7.31
Alkylate	vol%	6.51	6.27	5.38
Natural Gasoline	vol%	0.00	0.00	0.00
Reformer Feed	vol%	0.00	0.00	15.08
Reformate	vol%	43.30	43.46	24.76
FCC_Naphtha	vol%	26	25	22
Gasoline Volume	vol%	100	100	100

Steffen Mueller:
corrected to reflect comments on MTBE use

Table 10: Complex Model Results Tokyo

		Tokyo		
		ETBE	Ethanol-10	Ethanol-20
CHANGE FROM BASE		BASE-Tokyo		
Gasoline Volume - Relative	BPD	100.0	104.3	119.1
Hydrogen from Catalytic Reformer - Relative	MM SCF/day	51.7	36.7	27.5
Gasoline Volume Change from Base		0.0%	4.3%	19.1%
Hydrogen Volume Change from Base		0.0%	-29.0%	-46.8%
Catalytic Reforming Unit Octane (Severity)	RON	90.4	88.0	88.0
OXYGENATE MIX				
MTBE	vol%	0.00%	0.0%	0.0%
ETBE	vol%	6.42%	0.0%	0.0%
ETHANOL	vol%	0.0%	10.0%	20.0%
TAME	vol%	0.0%	0.0%	0.0%
GASOLINE PROPERTIES				
RON		91.5	91.5	94.9
MON		82.6	81.6	81.8
(R+M)/2		87.0	86.5	88.4
Specific Gravity		0.7818	0.7727	0.7665
Oxygen	wt%	1.0	3.6	7.2
Sulfur	ppm	7.2	6.9	6.2
RVP	psi	8.7	8.7	8.7
E200	vol%	36.0	43.0	52.3
E300	vol%	74.5	75.9	79.4
Aromatics	vol%	24.1	23.1	20.6
Olefins	vol%	16.1	15.5	13.8
Benzene	vol%	0.63	0.61	0.54
GASOLINE BLENDSTOCKS				
Butane	vol%	5.21	3.39	3.06
MTBE	vol%	0.00	0.00	0.00
ETBE	vol%	6.42	0.00	0.00
Ethanol	vol%	0.00	10.00	20.00
Light Straight Run Naphtha	vol%	2.85	2.73	2.39
Penex	vol%	0.00	0.00	0.00
Pen_DIH	vol%	0.00	0.00	0.00
Pen_PSA	vol%	0.00	0.00	0.00
Light Hydrocracked Naphtha	vol%	2.76	2.65	2.32
Light Coker Naphtha	vol%	0.00	0.00	0.00
Alkylate	vol%	4.23	4.06	3.56
Natural Gasoline	vol%	0.00	0.00	0.00
Reformer Feed	vol%	0.00	9.66	16.71
Reformate	vol%	42.13	32.61	21.40
FCC_Naphtha	vol%	36.40	34.89	30.57
Gasoline Volume	vol%	100.00	100.00	100.00
EMISSIONS - EPA COMPLEX MODEL				
VOC				
Exhaust	mg/mile	889.58	831.37	761.67
Non-exhaust	mg/mile	560.77	560.77	560.77
Total VOC	mg/mile	1450.35	1392.14	1322.44
NOx	mg/mile	1204.24	1197.66	1174.60
TOXICS				
Exhaust				
Benzene	mg/mile	29.48	25.17	20.01
Acetaldehyde	mg/mile	6.44	11.35	27.24
Formaldehyde	mg/mile	9.99	10.01	10.11
Butadiene	mg/mile	13.47	11.34	8.65
Polycyclics	mg/mile	2.98	2.79	2.56
Subtotal	mg/mile	62.35	60.66	68.57
Non-Ehxaust				
Benzene	mg/mile	2.59	2.49	2.21
Total Toxics	mg/mile	64.94	63.16	70.78

The graph below summarizes the relative trend in emissions factors from the Complex Model for E10 and E20. The trends are graphed in percent change relative to E0. These emissions can be interpreted as the model results that country specific refiners would derive by employing the US Complex Model and its underlying vehicle fleet. The air toxins (benzene, acetaldehyde, formaldehyde, 1,3 butadiene) derived from the Complex Model were multiplied by their respective cancer potency factors to derive weighted toxins (see Section 5.5 for more detail).



	E10	E20	E10	E20	E10	E20	E10	E20	E10	E20
	Beijing		Mexico City		New Delhi		Seoul		Tokyo	
🟦 THC	-1.4%	-4.6%	-1.7%	-6.3%	-3.9%	-5.6%	-4.2%	-8.2%	-4.0%	-8.8%
🟧 NOx	-0.2%	-1.7%	0.4%	-0.4%	-0.9%	-2.0%	-0.3%	-1.0%	-0.5%	-2.5%
⬜ Polycyclics	-2.7%	-8.6%	-2.5%	-9.5%	-6.6%	-9.4%	-7.0%	-13.7%	-6.5%	-14.4%
🟨 Weighted Toxins	-12.0%	-29.2%	-7.0%	-23.4%	-21.2%	-36.6%	-19.8%	-36.3%	-14.7%	-32.1%

Figure 6: Summary of Complex Model Emissions Factor Results for Ethanol Blends by City

5 Emissions Factors for Ethanol Based on Published Emissions Studies

This section summarizes some of the key ethanol-gasoline vehicle emissions studies detailed in the literature.

5.1 The Impact of Ethanol on Fuel Economy

Stein et al point out that while the energy content of ethanol is approximately 33% less than gasoline the difference can be partially offset by improved thermal efficiency [23]. The authors state that increased ethanol enables redesigned engines to operate at higher compressions ratios. The study cites Ford's Ecoboost direct injection engine tests that showed that 96 RON E20 at 11 .9: 1 CR provides comparable fuel economy. Stein restates that volumetric fuel economy can stay equal to gasoline for E20-E30 based on several efficiency effects including reduced enrichment with higher ethanol content, and improved efficiency at part loads due to reduced heat transfer losses with ethanol, as well as the above mentioned higher compression ratios.

In 2016 Oak Ridge National Laboratory conducted engine tests on different ethanol blends to demonstrate the fuel economy of different ethanol blends in dedicated engines with downsizing and down speeding [24]. Down speeding was achieved with larger drive wheels and a different differential. Downsizing was achieved with increased test weight. For E30 (101 RON) the results showed already a fuel economy gain of 5% for the unmodified vehicles and a fuel economy improvement of 10% for the modified (downsped/downsized vehicle) over the baseline E10. Furthermore, the results showed that a splash blended RON 97 with 15% ethanol already in an unmodified 2014 Ford Fiesta (non-FFV) vehicle with a small turbocharged direct-injection engine already showed quasi fuel economy parity for the US06 driving cycle. Also noteworthy is that these tests do not include further potential improvements from custom designed pistons to increase the compression ratio.

These recent research findings show that the lower energy density of ethanol will likely not be a significant detriment to fuel economy in properly designed fuels and modern engines and may even be a an advantage in future high octane dedicated engine designs. In iBEAM all emissions calculations revert to a per distance driven basis and are therefore independent of fuel economy.

5.2 Emissions Factors for NOx, THC, CO, and Selected Air Toxins

Hilton and Duddy (2009) studied criteria pollutant tailpipe emissions from running splash blended E20 versus gasoline using the FTP-75 federal test procedure in a fleet of vehicles ranging from model year 1998 to 2004. The study was funded by the U.S. Department of Transportation [25]. The emissions test results for the average fleet measurements are listed in the table below.

Table 11: Hilton and Duddy Emissions Factors

	E20
NOx	-2.4
THC	-13.7
CO	-23.2

A joint study between the National Renewable Energy Laboratory and Oak Ridge National Laboratory tested sixteen in-use, light-duty passenger vehicles [26].. All fuels were splash blended and vehicles were tested on the LA92 (unified) drive cycle. The vehicle model years ranged from 1999 through 2007 and corresponded to Tier 0, Tier 1, and Tier 2 models. The estimated change in emissions relative to E0 for the statistically significant observations is summarized in the table below. In this study oxides of nitrogen showed no significant change.

Table 12: NREL/ORNL Emissions Factors

		E10	E15	E20
NMHC	(%)	-12.04	-11.49	-15.13
CO	(%)	-14.98	-15.11	-12.31
Acetaldehyde	(mg/mi)	0.38	0.7	0.81
Formaldehyde	(mg/mi)	0.11	0.14	0.11
Fuel Economy	(%)	-3.68	-5.34	-7.71

A study by Suarez-Bertoa et al. (2015) conducted in the Vehicle Emission Laboratory (VELA) at the European Commission Joint Research Centre assessed regulated and unregulated emissions from a Euro 5a flex-fuel vehicle (model year 2012 with direct injection) tested with nine different hydrous and anhydrous ethanol containing fuel blends over the World harmonized Light-duty vehicle Test Cycle and the New European Driving Cycle [27]. Emissions trends were compared to a 5% ethanol baseline gasoline blend. The following emissions profiles were obtained:

Table 13: Suarez-Bertoa et al. Emissions Factors

	E5	E10	E15	E10 vs. E5	E15 vs. E5
	mg/km	mg/km	mg/km	%	%
THC	120	42	49.5	-65%	-59%
NMHC	104	33.5	39.5	-68%	-62%
CO	378.5	429	384	13%	1%
NOx	36	27.5	30.5	-24%	-15%
Formaldehyde	1	0.5	0.5	-50%	-50%
Acetaldehyde	2	3.5	4	75%	100%
Benzene	4.5	2	1.5	-56%	-67%
Toluene	16	5	4.5	-69%	-72%

Note: Emissions factors for E5, E10 and E15 averaged for the WLTC and NEDC.

A study by Karavalakis et al. (UC Riverside and Pacific Northwest Laboratory) also investigated the impact of ethanol blends on criteria and a suite of unregulated pollutants in a fleet of gasoline-powered light-duty vehicles. Model year vehicles ranging from 1984 to 2007 were tested on FTP protocols [28]. Emissions from the different ethanol blends (E10, E20, E50, and E85) were compared against CARB phase 2 certification fuel with 11% MTBE content (i.e. E0) and a CARB phase 3 certification fuel with a 5.7% ethanol content. The study found that in most test cases THC and NMHC emissions were lower with the ethanol blends. CO emissions were lower with ethanol blends for all vehicles. NOx emissions results were mixed, with some older vehicles showing increases with increasing ethanol level, while other vehicles showed either no impact or a slight, but not statistically significant, decrease. Acetaldehyde emissions increased with increasing ethanol levels while BTEX and 1,3-butadiene emissions decreased with ethanol blends compared to the E0 fuel.

We extracted the following emissions factors from the paper:

Table 14: Karavalakis et al. Emissions Factors

	Vehicle	E10	E20	Additional Citations from Study
NOx	1984 Toyota	+14%	+19.5%	
NOx	1993 Ford Festiva	+13.2%	+24.6%	
Nox	Newer Vehicles (1996 Honda Accord, 2000 Toyota Camry, 2007 Chevrolet Silverado)			“did not show statistically significant trends in NOx emissions, although ethanol blends generally had lower emissions than CARB 2.”
THC	1984 Toyota pickup.	-17.4%	-22.7%	
THC	1985 Nissan pickup	-8.1	-23%	
THC	Newer Vehicles			“Total THC/NMHC emissions are an order of magnitude lower for newer vehicles as compared to older vehicles for all fuels tested, as would be expected with the more advanced emission control technologies seen in new vehicles.”
CO	1984 Toyota		-72.2	
CO	1985 Nissan		-36.4	
CO	1996 Honda Accord		-32.8	
CO				“The general trend of decreasing CO emissions with increasing ethanol content is consistent with previous studies and reductions may be ascribed to the fuel-borne oxygen, which leans the air–fuel ratio and improves oxidation during combustion and over the catalyst.”
Benzene	1996 Honda Accord	-58%	-71%	

Benzene	2007 Chevy Silverado FFV	+1%	-1%	
1,3 Butadiene	1996 Honda Accord	-31%	-50%	
1,3 Butadiene	2007 Chevy Silverado FFV	-29%	-62%	
Acetaldehyde	1996 Honda Accord	71%	202%	
Acetaldehyde	2007 Chevy Silverado FFV	-39%	+/-0%	
Formaldehyde	2007 Chevy Silverado FFV	-44%	-36%	

Storey et al (2010) derived the following results for a 2007 Pontiac Solstice equipped with a 2.0 L, turbocharged across FTP and US06 driving cycles.

Table 15 Storey et al. Emissions Factors

	E0	E10	E20	E10	E20
	g/mile	g/mile	g/mile	% vs E0	% vs E0
NMHC	0.055	0.044	0.091	-20%	65%
Nox	0.031	0.018	0.009	-42%	-71%
CO	0.35	0.36	0.3	3%	-14%

For older vehicles the SAE 920326 study titled "Effects of Oxygenated Fuels and RVP on Automotive Emissions - Auto / Oil Air Quality Improvement Program" derives the results listed in the table below.

Table 16: SAE 920326 Emissions Factors

Tailpipe Toxins	**%** vs E0
THC Total	-4.9
NMHC	-5.9
CO	-13.4
NOx	5.1
Benzene	-11.5
1,3 –butadiene	-5.8
Formaldehyde	+19.3
Acetaldehyde	159

A relatively comprehensive study by Oak Ridge National Laboratory tested vehicles from six vehicle manufacturers and model years 2000 through 2009 including Tier 2 and pre-Tier 2 vehicles. Splash blended E10, E15 and E20 fuels were produced and emissions were compared against E0. Emissions were measured using the Federal Test Procedure (FTP) [29]. The findings are summarized below.

Table 17: ORNL 2012 Study Emissions Factors

	E10	E20
	median	median
CO (%)	-2.36%	-20.43%
NOx (%)	34.26%	12.32%
NMHC (%)	-7.02%	-17.05%
NMOG (%)	-1.36%	-0.90%

5.3 Emissions Factors for PM Emissions

PM emissions in the past have not been regulated for gasoline engines. However, increasing fuel efficiency standards have spurred the deployment of direct injection (DI) engines over traditional port fuel injection engines (PFI). Reports show that all current gasoline engine development utilizes direct injection. GDI technology is currently used on Audi, BMW, GM, Ford, Hyundai, Lexus, Mazda, Mini, Nissan, Porsche, VW and other vehicles (https://noln.net/2017/04/27/unintended-consequences-drive-gdi-engines-shops-part-7/)

Storey et al confirm that DI gasoline engines can produce higher levels of PM emissions than port fuel injection engines and potentially even more than diesels equipped with diesel particulate filters [30]. The authors used a 2007 Pontiac Solstice equipped with a 2.0 L, turbocharged, direct injection engine. Storey et al showed that by increasing the ethanol blend level from E0 to E20, the average mass emissions declined 30% and 42% over the FTP and US06, respectively. Measurements during hot cycle transient operation demonstrated that E20 also lowered particle number concentrations. The table below summarizes the emissions results from Storey et al:

Table 18: Storey et al PM Emissions Factors

	E0	E10	E20	E10	E20
	mg/mile	mg/mile	mg/mile	% vs E0	% vs E0
FTP	3.65	3.43	2.58	-6%	-29%
US06	15.1	14.11	8.79	-7%	-42%
Average				-6%	-36%

Relatively large PM reductions were also reported for high ethanol blends by Mariq et al. [31]. That study shows a possibly small (<20%) benefit in PM mass and particle number emissions for ethanol blends between 0% to 20% but statistically significant 30%–45% reduction in PM mass and number emissions for high ethanol content fuel >30%.

Aikawa and Jetter (2014) showed that fuel components with high double bond values to more readily form particulate. The DBE value for ethanol and paraffins such as isooctane is zero, whereas for aromatics it is in the range of four to seven. Therefore, aromatic hydrocarbons (which tend to have high DBE values and low vapor pressure) disproportionately contribute to PM formation, and increasing paraffin or ethanol content of the fuel tends to decrease PM. This observation was found to be true for both direct injection and port fuel injection engines. The studies used the FTP75 driving cycles [32].

In iBEAM we recognize the evolving research on PM emissions reductions with ethanol blends as follows: We apply the derived emissions reductions cited above from Storey et al to vehicles equipped with GDI engines. The GDI engine share of future vehicle populations can be changed within iBEAM.

5.4 Polycyclic Aromatic Hydrocarbons, PM2.5 and Ultrafine Particles

Increasingly, a subcategory of PM emissions, the fine particle pollution classes with particles less than 2.5 microns in diameter (PM2.5) and ultrafine particles with particles less than 0.1 microns have received significant attention in emissions research due their large impact on mortality and health (https://www.ncbi.nlm.nih.gov/pubmed/19590680). Kawanaka et al argue in their study that while the contributions of ultrafine particles to total PM mass were only 2.3% (1.3% for suburban environments) the contributions of ultrafine particles to PAH deposition in the very sensitive alveolar region of the lung were about 10-fold higher than those to total PM mass for both the roadside and suburban atmospheres. The authors conclude that these results indicate that ultrafine particles are significant contributors to the deposition of PAHs in the alveolar region of the lung, although the concentrations of ultrafine particles in the atmosphere are very low. [33] The authors state that several PAHs are known to be strong mutagens and potential human carcinogens. In iBEAM polycyclic are assessed via the Complex Model results for each city.

According to the US EPA a major component of PM2.5 are secondary organic aerosols (SOA) (https://www.epa.gov/air-research/secondary-organic-aerosol-soas-research). SOAs are produced through the interaction of sunlight, volatile organic compounds from vehicles and industrial emissions, plants, and other airborne chemicals. Studies show significant lung and heart health impacts associated with SOAs. Importantly, Benzene is a major contributor to SOAs. Bruns et al showed that for wood combustion, in some cases, oxidation products of phenol, naphthalene and benzene alone can comprise up to 80% of the observed SOA [34]. The pathways of benzene emissions are extremely complex but important to understand. According to Stein et al. Benzene is formed from either unburned fuel-borne benzene or benzene formed during combustion of other compounds found in gasoline. Borras et al studied the atmospheric transformations of VOCs with a focus on benzene. They showed two general aerosol formation routes of benzene photo oxidation: a) via the formation of phenol, promoting the formation of SOA intermediate and b) directed by nitrogen oxides, the production of a gaseous intermediate, perhaps a ring fragmentation product such as muconaldehyde which also induces the aerosol formation [35]. In iBEAM the effect of benzene is additionally counted towards its cancer potency (see section below).

5.5 Air Toxins and Cancer Risk Assessment

The California Test Procedure for Evaluating Substitute Fuels and Clean Fuels specifically requires a risk analysis for the four Toxic Air Contaminants (1,3 Butadiene, Benzene, formaldehyde, and acetaldehyde [36]. Lloyd and Denton compiled a report detailing all the cancer potency factors for many chemical compounds and the underlying cancer studies [37]. The relative potency factors for the four toxic air contaminants are listed below.

Table 19: Lloyd and Denton Cancer Potency Factors

Toxic Air Contaminant	Relative Potency
benzene	0.17
acetaldehyde	0.016
formaldehyde	0.035
1,3 butadiene	1

Unnasch et al. applied the cancer potency factors in their assessment of different fuel cycle pathways [38]. Stein et al state that combustion chemistry shows that the oxidation of ethanol does not produce 1,3 butadiene nor benzene. Therefore, higher levels of ethanol would reduce engine out emission of benzene and 1,3 butadiene but increase acetaldehyde and formaldehydes. However, when factoring in the relative toxicity levels (e.g. toxicity factors applied by the California Air Resource Board) 1,3 butadiene and benzene have much higher weights and therefore the weighted sum risk of all four compounds is lower with ethanol [23]. In iBEAM we apply the relative potency factors to the emissions from both gasoline and ethanol blends for the four toxic air contaminants.

5.6 Summary of Emissions Factors for Ethanol Blends

The table below summarizes the literature of vehicle studies with E10 and E20 ethanol blends. These derived emissions adjustments for ethanol blends are used in iBEAM. Note that the results show generally consistent decreases for THC/NMHC, consistent decreases for CO for the higher ethanol blends, with higher uncertainties for NOx reflected in the literature. For PM emissions adjustments from ethanol blends we show the data from Storey et al which is based on GDI engine tests. Therefore, iBEAM projects the GDI share of future vehicles and then applies the respective emissions adjustments for ethanol blends from that citation.

Table 20: Summary of Ethanol Emissions Factors

		E10	E20	
Hilton and Duddy	THC		-13.7%	
Karavalakis	THC	-12.8%	-22.9%	
Bertoa	THC	-65.0%	-59.0%	vs E5
SAE 1992	THC	-4.9%		
NREL	NMHC	-12.0%	-15.1%	
Storey	NMHC	-20.0%		
Bertoa	NMHC	-68.0%		vs E5
SAE 1992	NMHC	-5.9%		
ORNL 2012	NMHC	-7.0%	-17.1%	
ORNL 2012		-1.4%	-0.9%	
Average	THC/NMC	-21.9%	-21.5%	

		E10	E20	
Hilton and Duddy	CO		-23.2%	
Karavalakis	CO		-47.1%	
NREL	CO	-15.0%	-12.3%	
Storey	CO	3.0%	-14.0%	
Bertoa	CO	13.0%		vs E5
SAE 1992	CO	-13.4%		
ORNL 2012	CO	-2.4%	-20.4%	
Average	CO	-3.0%	-23.4%	

		E10	E20	
Hilton and Duddy	NOx		-2.4%	
Karavalakis	NOx	13.6%	22.1%	
Storey	Nox	-42.0%	-71.0%	
Bertoa	NOx	-24.0%		vs E5
SAE 1992	NOx	5.1%		
ORNL 2012	NOx	34.3%	12.3%	
Average	NOx	-11.8%	-17.1%	

Storey	PM	-6.0%	-36.0%	

		E10	E20	
SAE 1992	Benzene	-11.5%		
Bertoa	Benzene	-56.0%		vs E5
Karavalakis	Benzene	-29.0%	-36.0%	
Average	Benzene	-32.0%	-36.0%	

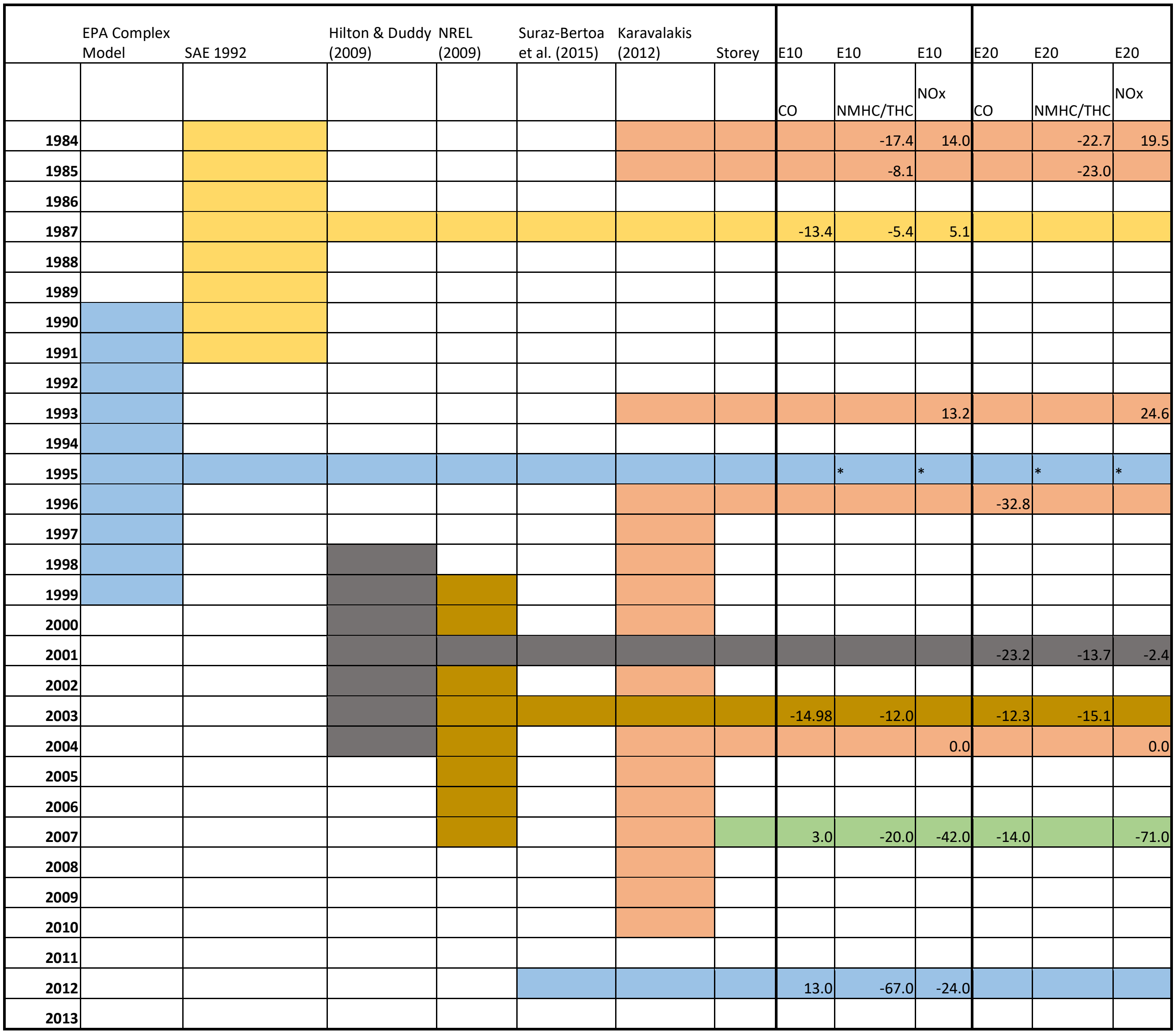
Karavalakis	1,3 –butadiene	-30.0%	-56.0%	
SAE 1992	1,3 –butadiene	-5.8%		
Average	1,3 –butadiene	-18.0%	-56.0%	

SAE 1992	Formaldehyde	19.3%		
Bertoa	Formaldehyde	-50.0%		vs E5
Karavalakis	Formaldehyde	-44.0%	-36.0%	
Average	Formaldehyde	-24.9%	-36.0%	

SAE 1992	Acetaldehyde	159.0%		
Bertoa	Acetaldehyde	75.0%		vs E5
Karavalakis	Acetaldehyde	16.0%	101.0%	
Average	Acetaldehyde	83.3%	101.0%	

6 Ethanol Emissions Factor Adjustments by Vehicle Age

Based on our literature review we grouped the studies by their employed vehicle fleet. Different colored cells in the figure below indicate the vehicle fleet years covered by the respective study. This forms the basis for a function in iBEAM that allows to account for the fact that different vintages of vehicles derive more or less emissions benefits from ethanol blended fuels.



	EPA Complex Model	SAE 1992	Hilton & Duddy (2009)	NREL (2009)	Suraz-Bertoa et al. (2015)	Karavalakis (2012)	Storey	E10	E10	E10	E20	E20	E20
								CO	NMHC/THC	NOx	CO	NMHC/THC	NOx
1984		🟨				🟧	🟧	🟧	-17.4	14.0	🟧	-22.7	19.5
1985		🟨				🟧	🟧	🟧	-8.1	🟧	🟧	-23.0	🟧
1986		🟨											
1987		🟨	🟨	🟨	🟨	🟨	🟨	-13.4	-5.4	5.1	🟨	🟨	🟨
1988		🟨											
1989		🟨											
1990	🟦	🟨											
1991	🟦	🟨											
1992	🟦												
1993	🟦					🟧	🟧	🟧	🟧	13.2	🟧	🟧	24.6
1994	🟦												
1995	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	*	*	🟦	*	*
1996	🟦					🟧	🟧	🟧	🟧	🟧	-32.8	🟧	🟧
1997	🟦					🟧							
1998	🟦		⬛			🟧							
1999	🟦		⬛	🟫		🟧							
2000			⬛	🟫		🟧							
2001			⬛	⬛	⬛	⬛	⬛	⬛	⬛	⬛	-23.2	-13.7	-2.4
2002			⬛	🟫		🟧							
2003			⬛	🟫	🟫	🟫	🟫	-14.98	-12.0	🟫	-12.3	-15.1	🟫
2004			⬛	🟫		🟧	🟧	🟧	🟧	0.0	🟧	🟧	0.0
2005				🟫		🟧							
2006				🟫		🟧							
2007				🟫		🟧	🟩	3.0	-20.0	-42.0	-14.0	🟩	-71.0
2008						🟧							
2009						🟧							
2010						🟧							
2011													
2012					🟦	🟦	🟦	13.0	-67.0	-24.0	🟦	🟦	🟦
2013													

*Assessed by city based on fuel samples

Figure 7: Ethanol Emissions Literature Summary by Vehicle Fleet Age

We have set up a linear and a non-linear adjustment option. In addition to the studies above we added the emissions factors developed from the EPA Complex Model for each city in the regression model. This way we ensured a city-specific contribution to the overall emissions assessment while taking into account the underlying vehicle fleet. Note that the current linear adjustment in iBEAM reverts back to the average of all studies for the individual pollutants (with additional weight on the complex model results). The non-linear adjustments allows for a more conservative estimate of emissions reductions from ethanol relative to gasoline. We further concluded that effects from ethanol on NOx emissions across all studies is not statistically significant and therefore a true zero.

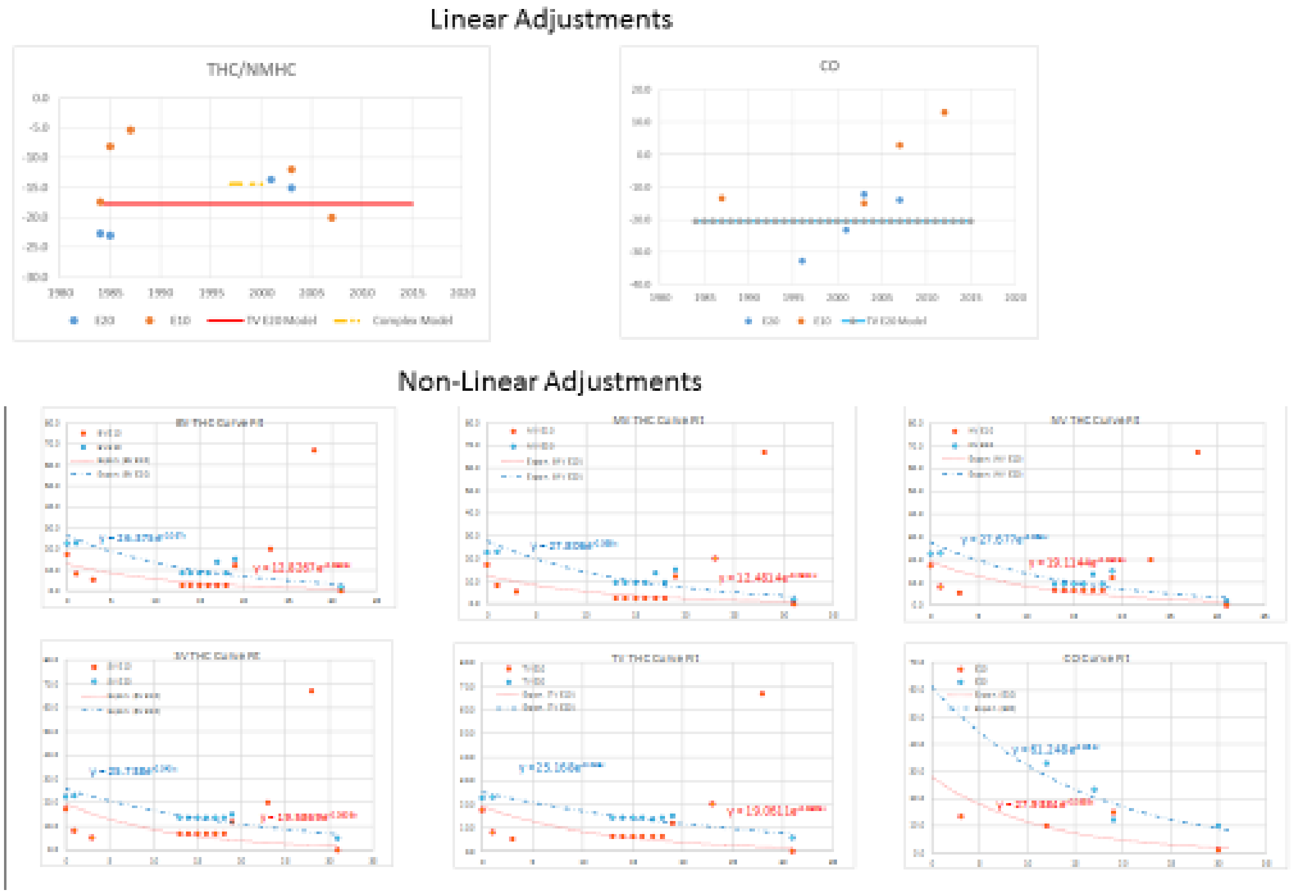
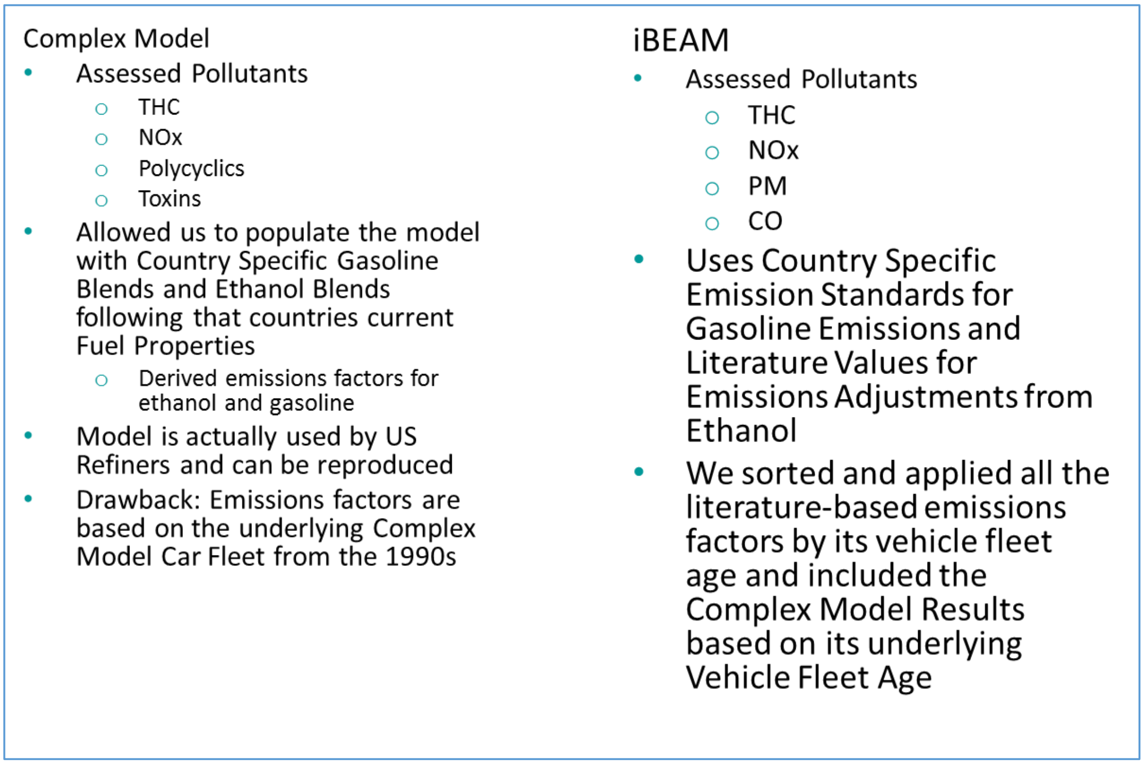


Figure 8: Emissions Factor Adjustment Equations by Vehicle Age

The figure below futher illustrates the integration of the Complex Model emissions factors with iBEAM



Complex Model

- Assessed Pollutants
    - THC
    - NOx
    - Polycyclics
    - Toxins
- Allowed us to populate the model with Country Specific Gasoline Blends and Ethanol Blends following that countries current Fuel Properties
    - Derived emissions factors for ethanol and gasoline
- Model is actually used by US Refiners and can be reproduced
- Drawback: Emissions factors are based on the underlying Complex Model Car Fleet from the 1990s

iBEAM

- Assessed Pollutants
    - THC
    - NOx
    - PM
    - CO
- Uses Country Specific Emission Standards for Gasoline Emissions and Literature Values for Emissions Adjustments from Ethanol
- We sorted and applied all the literature-based emissions factors by its vehicle fleet age and included the Complex Model Results based on its underlying Vehicle Fleet Age

Figure 9: Integration of the Complex Model Emissions Factors with iBEAM

7 Emissions Factor Development for Gasoline Exhaust Emissions Based on Standards

In this emissions factor approach we assumed that all gasoline passenger cars follow the permissible limits for the given standard. The table below lists the major sources and citations for the current and predicted standards. Appendix A lists the employed values for each city. When there is an offset of one month or less in the implementation date of a new standard in a year, the standard has been rounded off to be followed through for the whole year.

Table 21: Sources of Gasoline Emissions Factors based on Standards

City	**Citation**	**Notes**
Beijing	• "Beijing: Light-Duty: Emissions," icct and DieselNet, [Online]. Available: http://transportpolicy.net/index.php?title=Beijing:_Light-Duty:_Emissions. • K. Derla, "China Capital Beijing To Implement World's Strictest Vehicle Emission Standards By 2017," 26 May 2016. [Online]. Available: http://www.techtimes.com/articles/161103/20160526/china-capital-beijing-to-implement-worlds-strictest-vehicle-emission-standards-by-2017.htm.	The first citation gives the standards for Beijing. The second citation gives the implementation date for Beijing 6. **To show consistency between the studies, Euro 1-3 has been adopted for NOx and HC emissions.**
Mexico City	• https://www.dieselnet.com/standards/mx/ld.php	The data has been obtained from the citation. Citation also gives phase in schedules, which is ignored due to the incremental set up done in the model- the implementation dates have still been considered. **THC values have been taken for LDV and LDT.** **Mexico City has not defined future standards, the present standards have been used going forward in the study.**

New Delhi	• "India Light duty vehicles emissions," [Online]. Available: http://transportpolicy.net/index.php?title=India:_Light-duty:_Emissions . [Accessed 22 June 2017]	Data has been obtained from the citation. The implementation dates are obtained from the same citation too. **New Delhi will be changing from BS IV to BS VI in 2020, rapid advances to keep the standards in line with global standards.**
Seoul	• "South Korea: Light-duty: Emissions," ICCT and DieselNet, [Online]. Available: http://transportpolicy.net/index.php?title=South_Korea:_Light-duty:_Emissions . [Accessed 27 June 2017] • https://www.delphi.com/docs/default-source/worldwide-emissions-standards/delphi-worldwide-emissions-standards-passenger-cars-light-duty-2016-7.pdf	Citations give the limits for the years starting from 2009. **Seoul has not defined any prospective standard going forward. The standards are more stringent compared to Euro 6, so going forward from 2020, limits have been kept in par with Euro 6, at least. A taper has been assumed for NMOG emissions, which has been accessed from the second citation.**
Tokyo	• Transport Policy, "Japan: Light-duty: Emissions," 11 September 2013. [Online]. Available: http://transportpolicy.net/index.php?title=Japan:_Light-duty:_Emissions . [Accessed 26 July 2017]. • https://www.env.go.jp/en/air/aq/mv/table_290628.pdf	The first citation gives the present standards for Tokyo. The second citation is the English translated future standards prescribed for Tokyo. **Tokyo has changed its testing method from JC08 to WLTC, thus there is a discrepancy in the limits from 2017 to 2018.**

In order to facilitate a consistent comparison of our derived emissions standards we graphed the combined [hydrocarbon (HC) plus NOx] emissions standards for each city below. All cities show dramatic reductions in permissible emissions with Mexico City and New Delhi lagging behind in the earlier years.

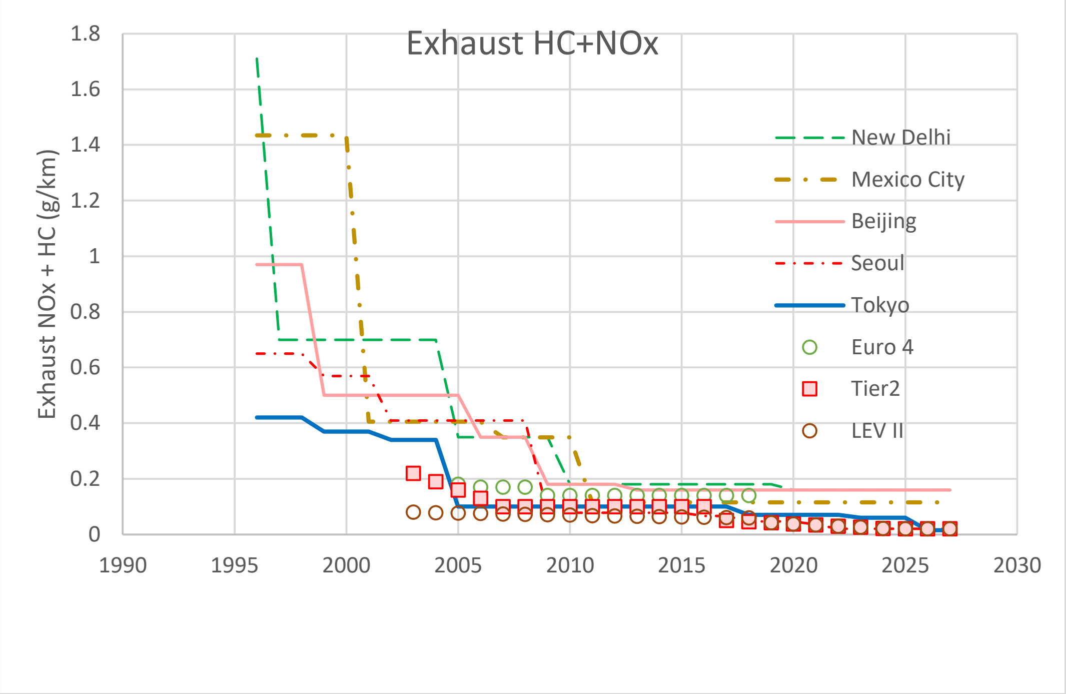


Figure 10: Summary of Exhaust HC+NOx Emissions Standards by City

Regulating particulate matter for gasoline engines in the future is currently a subject of debate and technical evaluation especially in light of the higher PM emissions associated with gasoline direct injection engines. In the absence of emissions standards and an effort to evaluate PM emissions consistently for all the cities we have used the PM emissions factors from the EPA MOVES2014 study [39], which has been derived from the 2004/05 Kansas City study [40]. The table below lists the emissions factors for PM used for all cities

Table 22: PM Emissions Factors MOVES

Year range	PM Factor (mg/km)
2000-2016	1.56
2016-2020	1.25
2021-2027	0.93

8 THC Evaporative Emissions for Gasoline and Ethanol

This section discusses evaporative HC emissions in addition to tailpipe emissions. These emissions include venting and leaks from the evaporative emissions, emissions during vehicle fueling, and permeation of fuel through the fuel system components. The figure below shows the total evaporative emission sources from a vehicle.

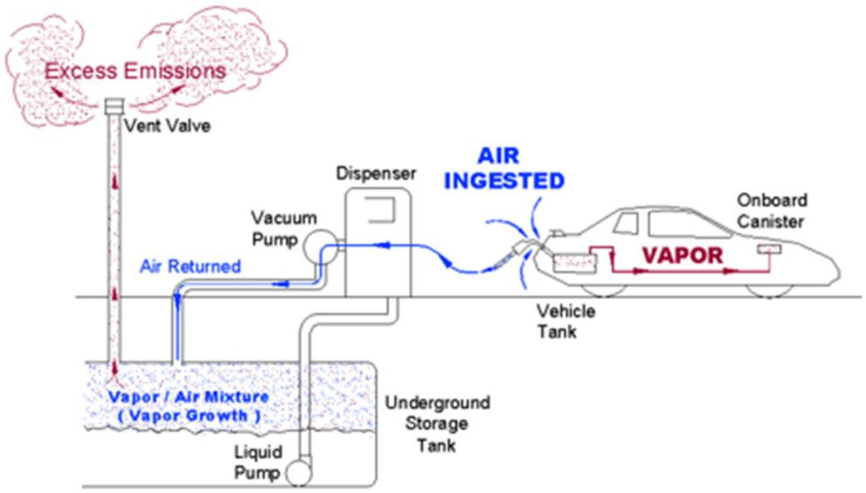


Figure 11: Evaporative Emissions Components (Source: California Air Resources Board)

Venting emissions include diurnal breathing and running losses. The venting emissions are represented by evaporative emission standards with tests that correspond to a sealed housing for evaporative determination (SHED). The evaporative emission standards are regulated in each country. The roll-in of emission standards over time is estimated based on published standards [41] [42]. The figure below shows the employed evaporative emissions factors for each city. The values are listed in Appendix A.

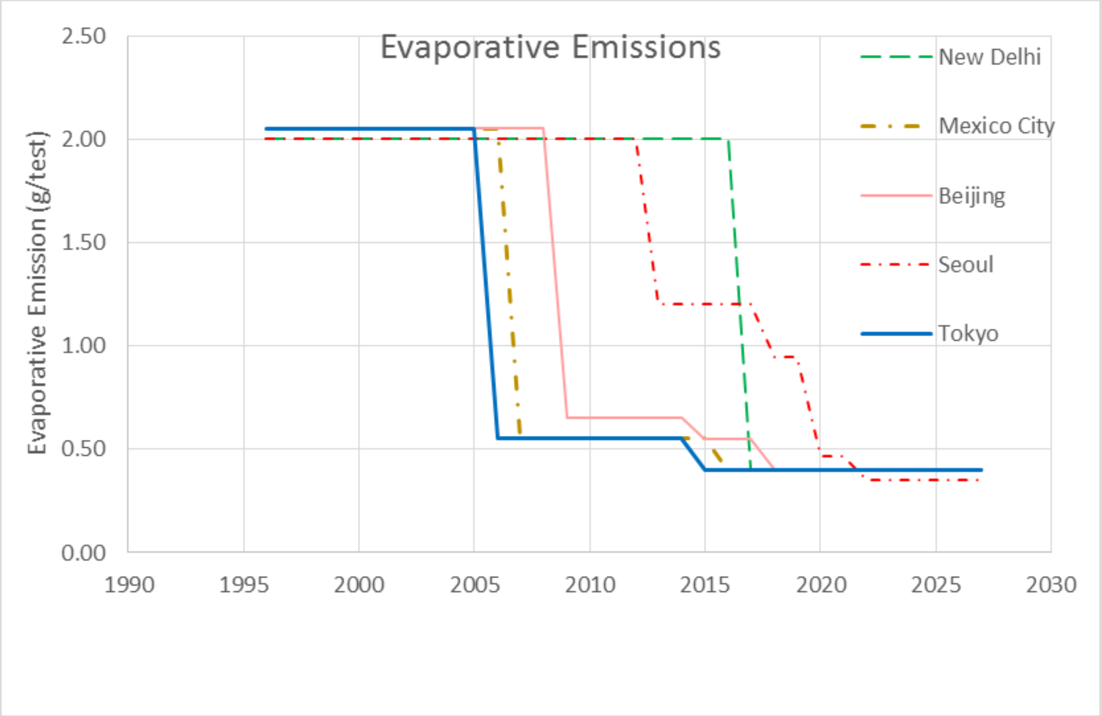
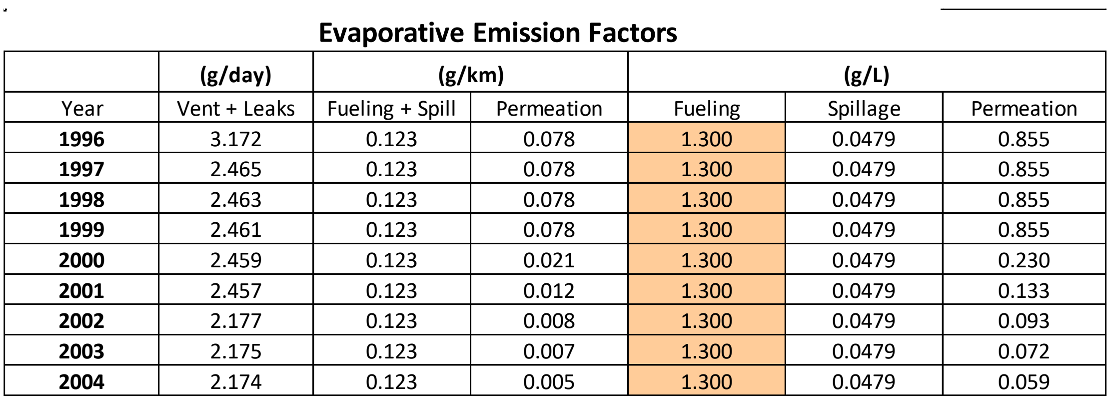


Figure 12: Summary of Evaporative Emissions Standards by City

Vehicle fuel systems also include leaks. The ratio of leaks to venting from MOVES model runs provides the basis for estimating leaks. The table below shows an example of the evaporative emissions in grams per day for selected years.



Evaporative Emission Factors

	(g/day)	(g/km)		(g/L)		
Year	Vent + Leaks	Fueling + Spill	Permeation	Fueling	Spillage	Permeation
1996	3.172	0.123	0.078	1.300	0.0479	0.855
1997	2.465	0.123	0.078	1.300	0.0479	0.855
1998	2.463	0.123	0.078	1.300	0.0479	0.855
1999	2.461	0.123	0.078	1.300	0.0479	0.855
2000	2.459	0.123	0.021	1.300	0.0479	0.230
2001	2.457	0.123	0.012	1.300	0.0479	0.133
2002	2.177	0.123	0.008	1.300	0.0479	0.093
2003	2.175	0.123	0.007	1.300	0.0479	0.072
2004	2.174	0.123	0.005	1.300	0.0479	0.059

Figure 13: Example of Evaporative Emissions Components in iBEAM

In addition to venting and leaks, emissions occur from permeation though the fuel system material such as hoses and gaskets. Permeation emissions are estimated as a function of model year from MOVES model results. Permeation emissions have improved significantly over the past 20 years and the introduction of low permeation materials is a model input for each city (see figure below). Ethanol blends have affected permeation emissions with generally higher emissions from ethanol blend. The emissions from ethanol vehicles are estimated from the ratio of E10 to gasoline/MTBE blends from the MOVES model.

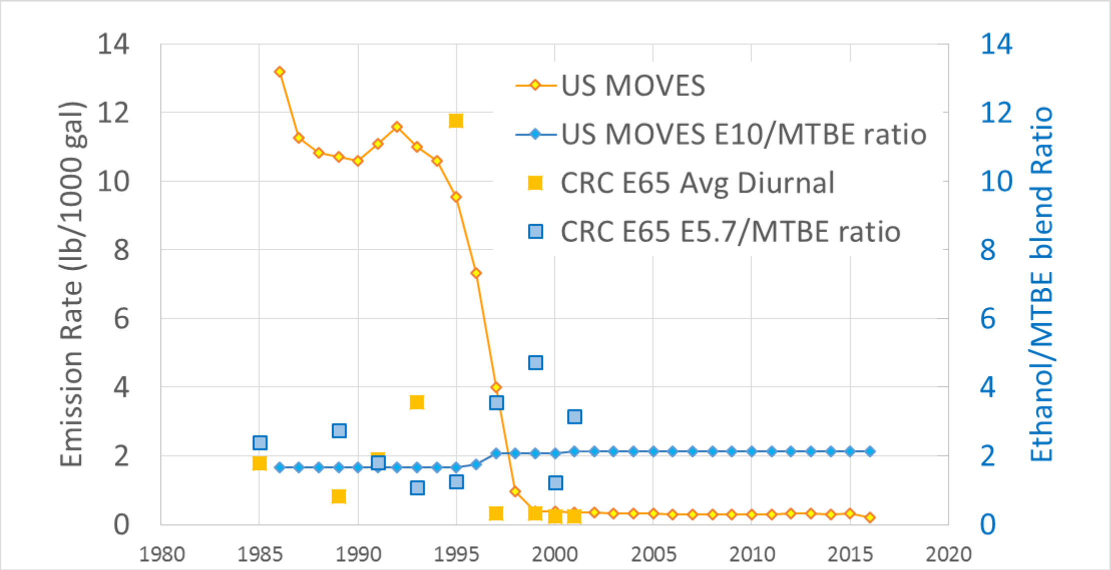
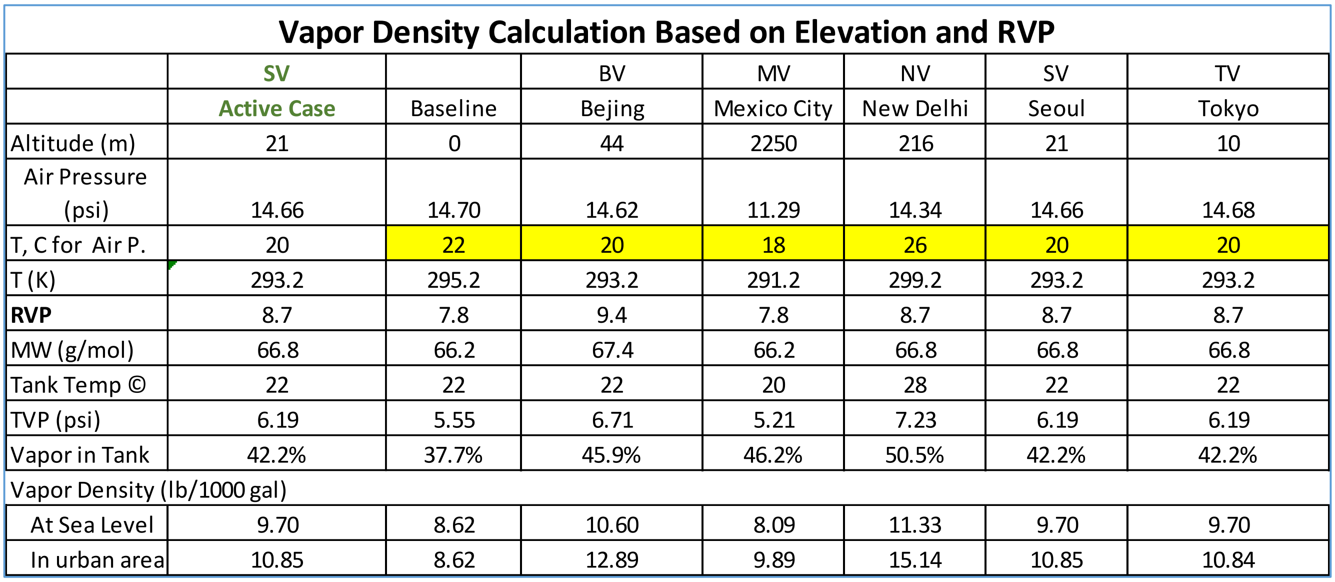


Figure 14: Improvements in Permeation Emissions over Time

Refueling emissions include vapor displacement from the vehicle fuel tank. Fuel displaces vapors in the fuel tank. These vapors are either released into the atmosphere, captured with Stage 2 vapor recovery at the fuel station, or captured with on-board refueling vapor recovery (ORVR). The effectiveness of State 2 vapor recovery and ORVR are model represented by the fraction of vapors that are released. The utilization and effectiveness of Stage 2 vapor recovery and ORVR is an input for each city. Emissions of refueling emissions are calculated from the total vehicle fuel consumed based on fuel economy projections and the evaporative emissions per liter of fuel.

The density of fuel vapors in the vehicle fuel tank depends upon the vapor pressure of the fuel at fuel tank conditions combined with altitude (see figure below). The vapor density was calculated from the parameters in the table below. The true vapor pressure (TVP) is a function of Reid Vapor Pressure, molecular weight, and fuel tank temperature based on correlations from the California ARB. Molecular weight of the vapors is also dependent on the fuel RVP with slightly lower molecular weights corresponding to higher RVP fuels. The vapor density in the tank depends on altitude, the fuel’s TVP, and molecular weight. The vapor density corresponds to the TVP of the fuel/air pressure at altitude, which is calculated for the elevation of each city.



Vapor Density Calculation Based on Elevation and RVP

	SV		BV	MV	NV	SV	TV
	Active Case	Baseline	Bejing	Mexico City	New Delhi	Seoul	Tokyo
Altitude (m)	21	0	44	2250	216	21	10
Air Pressure (psi)	14.66	14.70	14.62	11.29	14.34	14.66	14.68
T, C for Air P.	20	22	20	18	26	20	20
T (K)	293.2	295.2	293.2	291.2	299.2	293.2	293.2
RVP	8.7	7.8	9.4	7.8	8.7	8.7	8.7
MW (g/mol)	66.8	66.2	67.4	66.2	66.8	66.8	66.8
Tank Temp ©	22	22	22	20	28	22	22
TVP (psi)	6.19	5.55	6.71	5.21	7.23	6.19	6.19
Vapor in Tank	42.2%	37.7%	45.9%	46.2%	50.5%	42.2%	42.2%
Vapor Density (lb/1000 gal)							
At Sea Level	9.70	8.62	10.60	8.09	11.33	9.70	9.70
In urban area	10.85	8.62	12.89	9.89	15.14	10.85	10.84

Figure 15: City Specific Parameters for Refueling Emissions Calculations

9 Emissions Deterioration Factors

Vehicle emissions deteriorate over the lifetime of a vehicle. A recent report by TNO Netherlands in cooperation with International Institute for Applied Systems Analysis (IIASA) in Austria estimates deterioration factors for EURO 1 and EURO 2 vehicles from data collected over several years from 166 vehicles (96 different models) [43]. The report concludes that the deterioration factors are almost double from their previous work. We have adopted their published values (listed in Table 1 of that publication). The TNO factors seem to be consistent with factors published in another recent paper by Borken-Klefeld and Chen which are assessed as a function of mileage driven (see Table 2 of that publication) [44].

10 Emissions Results

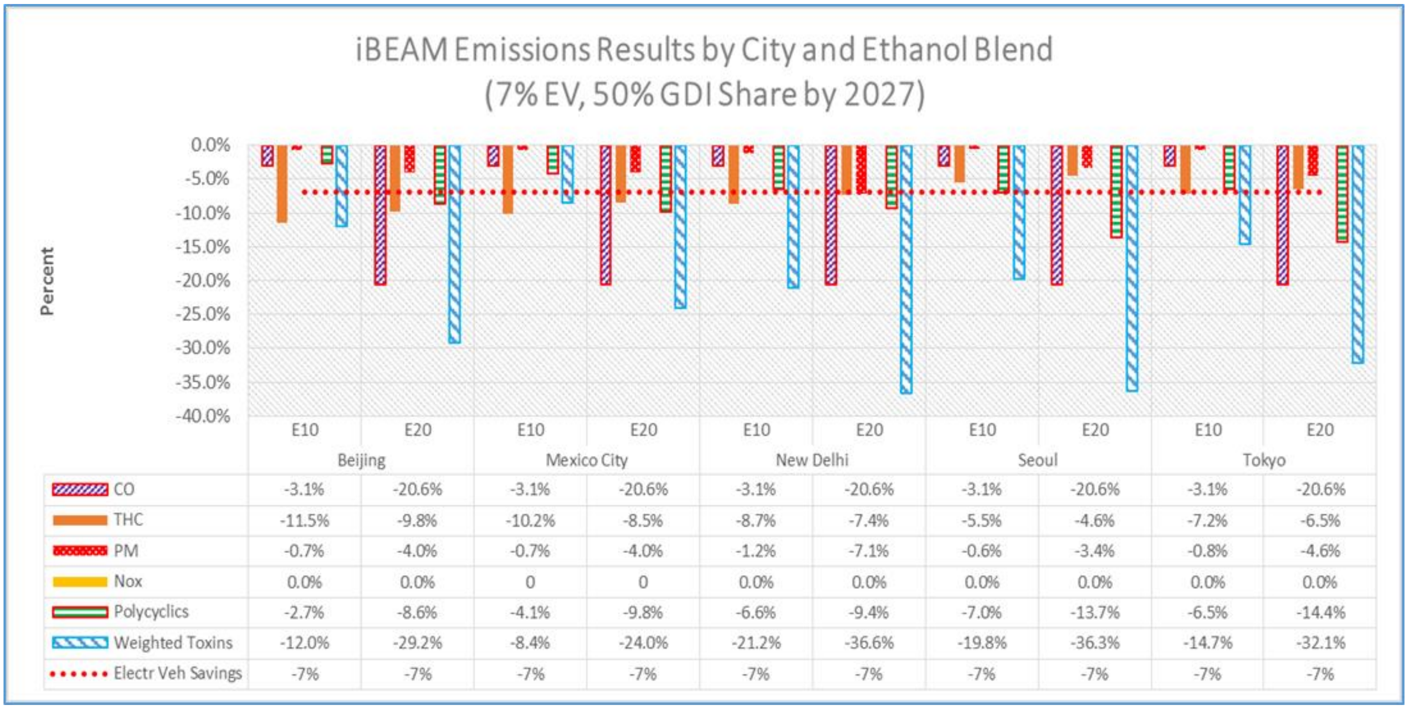
In this section we summarize the emissions adjustments in tonnes and percent by city and by ethanol blend (see figure below). Furthermore, we show the main model inputs and outputs. The model inputs shown for each city below include the projected number of gasoline vehicles and their EV share, the project fuel use and fuel economy as well as the vehicle distance travelled. The model outputs list the key pollutants emitted in tonnes by year (and totals over the time frame) and the percent reductions in air toxins and polycyclic.

On a total tonnage and percentage basis through the year 2027 the results show hydrocarbon (THC, VOC) reductions across all cities from E10 and E20 blends which should result in reduced risk for ozone formation in these cities. Furthermore, the study finds significant polycyclics and weighted toxins reductions (often correlated with cancer) and reduced CO emissions which reduces heart disease and other health effects. The study also shows that NOx emissions remain unaffected by ethanol blends.

The results are also particularly relevant in light of the current debate on electric vehicle deployment. Since iBEAM enables a selection of different EV adoption scenarios we can compare the emissions savings from ethanol blends to the emissions savings expected with EVs. Note that these are tailpipe emissions only and do not include any upstream emissions from electricity production which, in many of the studied countries, may come from coal fired power plants. The comparison between ethanol and EV (dashed red line in graph below) shows that EV vehicles through 2027 will just about save the same amount of THC/VOC emissions as a fleet change to E10 and E20 would produce and that EV vehicles will provide significantly less savings for carbon monoxides and weighted toxins through 2027.

Table 23: Summary of Emissions in Tons by City and Ethanol Blend

	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	0	0	0	0	0	0	0	0	0	0



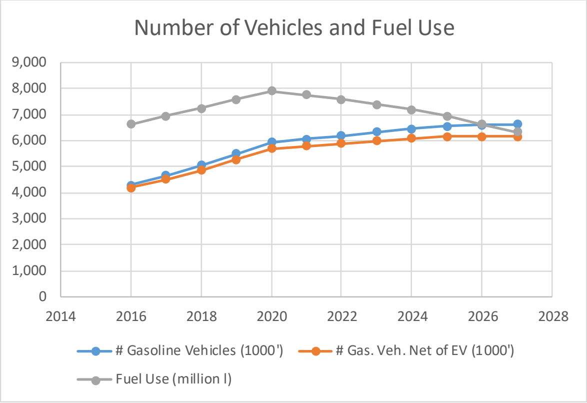
	Beijing E10	Beijing E20	Mexico City E10	Mexico City E20	New Delhi E10	New Delhi E20	Seoul E10	Seoul E20	Tokyo E10	Tokyo E20
▨ CO	-3.1%	-20.6%	-3.1%	-20.6%	-3.1%	-20.6%	-3.1%	-20.6%	-3.1%	-20.6%
■ THC	-11.5%	-9.8%	-10.2%	-8.5%	-8.7%	-7.4%	-5.5%	-4.6%	-7.2%	-6.5%
■ PM	-0.7%	-4.0%	-0.7%	-4.0%	-1.2%	-7.1%	-0.6%	-3.4%	-0.8%	-4.6%
■ Nox	0.0%	0.0%	0	0	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
▭ 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%
•••••• Electr Veh Savings	-7%	-7%	-7%	-7%	-7%	-7%	-7%	-7%	-7%	-7%

Figure 16: Summary of Emissions in Percent by City and Ethanol Blend

iBEAM Output Beijing E10

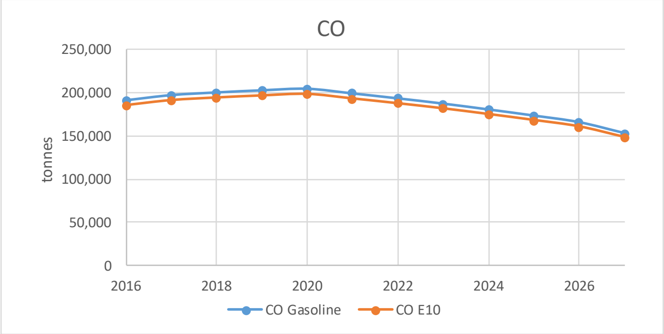
GDI Rate: 50% **EV Rate: 7%**

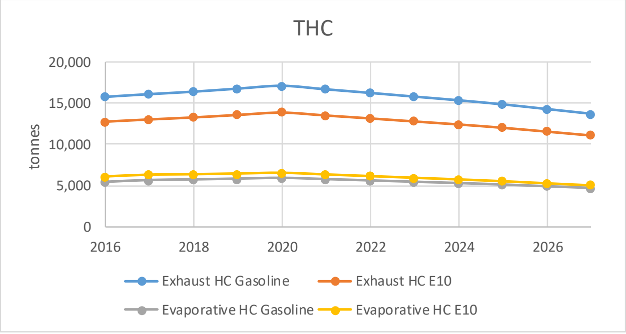
Year	# Gasoline Vehicles (1000')	# Gas. Veh. Net of EV (1000')	Fuel Use (million l)	FE (l/100 km)	VDT (million km/year)
2016	4,294	4,177	6,623	9.44	70,174
2017	4,659	4,514	6,941	9.26	74,936
2018	5,040	4,864	7,248	9.09	79,762
2019	5,483	5,270	7,593	8.89	85,370
2020	5,933	5,679	7,911	8.71	90,869
2021	6,062	5,779	7,751	8.61	89,986
2022	6,193	5,880	7,577	8.51	89,035
2023	6,326	5,982	7,389	8.40	88,015
2024	6,462	6,085	7,186	8.27	86,923
2025	6,560	6,152	6,940	8.14	85,242
2026	6,592	6,157	6,635	8.03	82,675
2027	6,625	6,161	6,330	7.90	80,096



tonnes

Year	CO		Exhaust HC		Evaporative HC		NOx		PM	
	Gasoline	E10	Gasoline	E10	Gasoline	E10	Gasoline	E10	Gasoline	E10
2016	191,235	185,317	15,779	12,790	5,409	6,082	16,630	16,630	110	109
2017	197,253	191,148	16,112	13,060	5,623	6,280	16,792	16,792	115	115
2018	200,359	194,158	16,412	13,303	5,691	6,331	16,892	16,892	120	120
2019	202,844	196,566	16,785	13,606	5,783	6,410	16,995	16,995	126	126
2020	204,661	198,326	17,133	13,888	5,870	6,485	17,043	17,043	133	132
2021	199,229	193,063	16,700	13,536	5,725	6,305	16,495	16,495	129	129
2022	193,473	187,485	16,262	13,182	5,575	6,121	15,938	15,938	126	125
2023	187,355	181,556	15,807	12,813	5,423	5,937	15,373	15,373	123	122
2024	180,544	174,956	15,356	12,447	5,273	5,756	14,814	14,814	119	118
2025	173,428	168,061	14,858	12,044	5,104	5,557	14,232	14,232	115	114
2026	165,765	160,634	14,283	11,578	4,905	5,325	13,606	13,606	111	110
2027	153,071	148,333	13,706	11,110	4,711	5,101	12,982	12,982	106	105
Total:	2,249,216	2,179,603	189,192	153,356	65,091	71,690	187,794	187,794	1,434	1,424
Savings		-69,613		-35,837		6,599		0		-10





	Relative to E0 (%)	Relative to E0 (Total Tonnes)
CO	-3.1%	-69,613
THC	-11.5%	-29,238
PM	-0.7%	-10
NOx	0	0
Polycyclics	-2.7%	
Weighted Toxins	-12.0%	

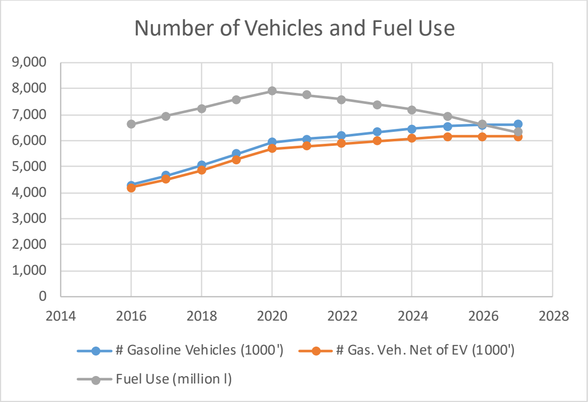
From Complex Model
Based on Fuel Samples

Toxic Air Contaminant	Relative Potency	Toxics Mass Change
benzene	0.17	-14.6%
acetaldehyde	0.02	163.8%
formaldehyde	0.04	-3.9%
1,3 butadiene	1.00	-12.0%
Polycyclics	0.00	-2.7%
Total Weighted:		-12.0%

iBEAM Output Beijing E20

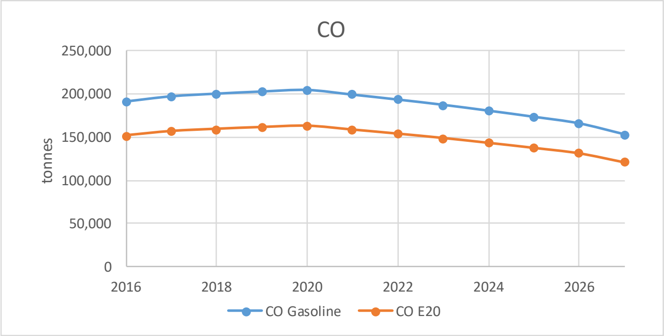
GDI Rate: 50% | **EV Rate: 7%**

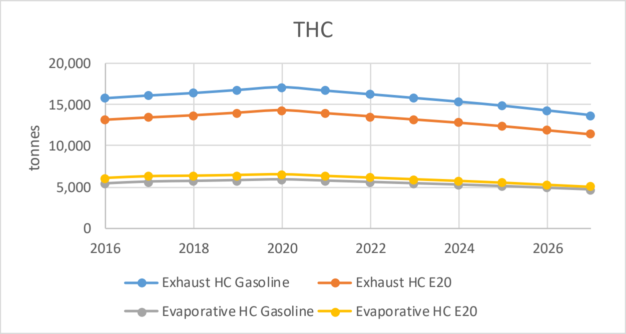
Year	# Gasoline Vehicles (1000')	# Gas. Veh. Net of EV (1000')	Fuel Use (million l)	FE (l/100 km)	VDT (million km/year)
2016	4,294	4,177	6,623	9.44	70,174
2017	4,659	4,514	6,941	9.26	74,936
2018	5,040	4,864	7,248	9.09	79,762
2019	5,483	5,270	7,593	8.89	85,370
2020	5,933	5,679	7,911	8.71	90,869
2021	6,062	5,779	7,751	8.61	89,986
2022	6,193	5,880	7,577	8.51	89,035
2023	6,326	5,982	7,389	8.40	88,015
2024	6,462	6,085	7,186	8.27	86,923
2025	6,560	6,152	6,940	8.14	85,242
2026	6,592	6,157	6,635	8.03	82,675
2027	6,625	6,161	6,330	7.90	80,096



tonnes

Year	CO		Exhaust HC		Evaporative HC		NOx		PM	
	Gasoline	E20	Gasoline	E20	Gasoline	E20	Gasoline	E20	Gasoline	E20
2016	191,235	151,884	15,779	13,154	5,409	6,082	16,630	16,630	110	108
2017	197,253	156,663	16,112	13,432	5,623	6,280	16,792	16,792	115	113
2018	200,359	159,130	16,412	13,682	5,691	6,331	16,892	16,892	120	117
2019	202,844	161,104	16,785	13,993	5,783	6,410	16,995	16,995	126	122
2020	204,661	162,547	17,133	14,284	5,870	6,485	17,043	17,043	133	128
2021	199,229	158,233	16,700	13,922	5,725	6,305	16,495	16,495	129	124
2022	193,473	153,661	16,262	13,558	5,575	6,121	15,938	15,938	126	121
2023	187,355	148,802	15,807	13,178	5,423	5,937	15,373	15,373	123	117
2024	180,544	143,392	15,356	12,802	5,273	5,756	14,814	14,814	119	113
2025	173,428	137,741	14,858	12,387	5,104	5,557	14,232	14,232	115	109
2026	165,765	131,655	14,283	11,908	4,905	5,325	13,606	13,606	111	104
2027	153,071	121,572	13,706	11,426	4,711	5,101	12,982	12,982	106	99
Total:	2,249,216	1,786,383	189,192	157,728	65,091	71,690	187,794	187,794	1,434	1,376
Savings		-462,832		-31,464		6,599		0		-58





	Relative to E0 (%)	Relative to E0 (Total Tonnes)
CO	-20.6%	-462,832
THC	-9.8%	-24,866
PM	-4.0%	-58
NOx	0	0
Polycyclics	-8.6%	
Weighted Toxins	-29.2%	

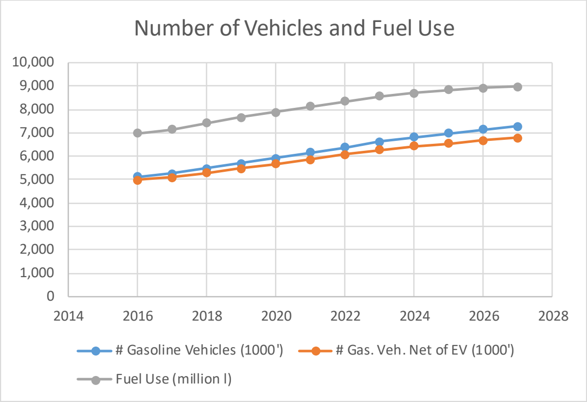
From Complex Model
Based on Fuel Samples

Toxic Air Contaminant	Relative Potency	Toxics Mass Change
benzene	0.17	-32.6%
acetaldehyde	0.02	544.8%
formaldehyde	0.04	-3.9%
1,3 butadiene	1.00	-32.1%
Polycyclics	0.00	-8.6%
Total Weighted:		-29.2%

iBEAM Output	Mexico (E10

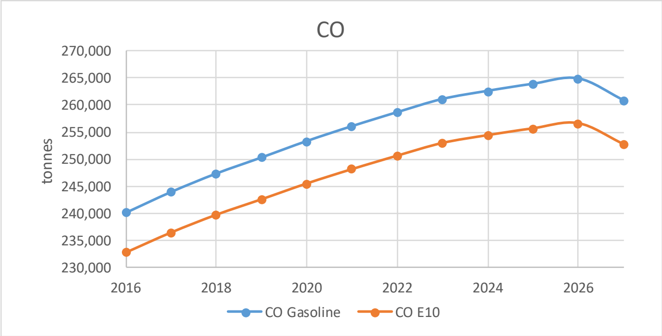
GDI Rate: 50%	EV Rate: 7%

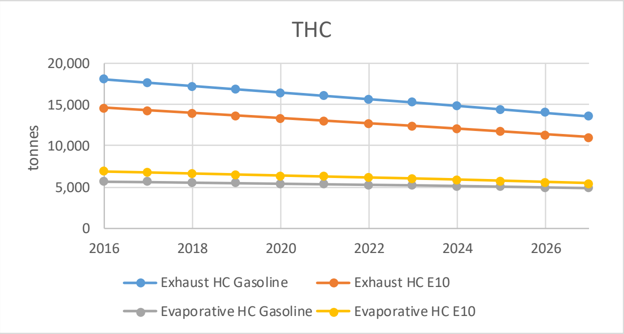
Year	# Gasoline Vehicles (1000')	# Gas. Veh. Net of EV (1000')	Fuel Use (million l)	FE (l/100 km)	VDT (million km/year)
2016	5,114	4,975	6,964	8.58	81,131
2017	5,268	5,104	7,153	8.51	84,014
2018	5,481	5,289	7,404	8.43	87,876
2019	5,698	5,477	7,650	8.33	91,840
2020	5,920	5,667	7,889	8.23	95,906
2021	6,151	5,864	8,123	8.11	100,142
2022	6,387	6,064	8,348	7.99	104,488
2023	6,628	6,267	8,561	7.86	108,948
2024	6,817	6,419	8,708	7.73	112,586
2025	6,988	6,553	8,824	7.61	115,934
2026	7,136	6,664	8,905	7.49	118,927
2027	7,288	6,777	8,974	7.36	121,993



tonnes

Year	CO		Exhaust HC		Evaporative HC		NOx		PM	
	Gasoline	E10	Gasoline	E10	Gasoline	E10	Gasoline	E10	Gasoline	E10
2016	240,214	232,779	18,071	14,610	5,699	6,932	52,726	52,726	127	126
2017	244,013	236,461	17,668	14,284	5,650	6,813	51,181	51,181	130	129
2018	247,398	239,741	17,276	13,967	5,579	6,675	49,515	49,515	134	134
2019	250,342	242,594	16,881	13,648	5,510	6,541	47,804	47,804	139	138
2020	253,349	245,508	16,494	13,335	5,442	6,409	46,096	46,096	143	142
2021	256,081	248,155	16,096	13,013	5,371	6,276	44,320	44,320	146	145
2022	258,641	250,637	15,702	12,695	5,304	6,149	42,578	42,578	148	147
2023	261,063	252,983	15,315	12,382	5,241	6,026	40,818	40,818	151	150
2024	262,551	254,425	14,903	12,049	5,158	5,882	39,030	39,030	153	151
2025	263,841	255,675	14,485	11,711	5,070	5,733	37,241	37,241	154	153
2026	264,842	256,646	14,058	11,365	4,974	5,573	35,452	35,452	155	154
2027	260,876	252,802	13,640	11,028	4,879	5,416	33,774	33,774	156	155
Total:	3,063,212	2,968,406	190,588	154,087	63,877	74,425	520,535	520,535	1,736	1,725
Savings		-94,806		-36,501		10,548		0		-11





	Relative to E0 (%)	Relative to E0 (Total Tonnes)
CO	-3.1%	-94,806
THC	-10.2%	-25,953
PM	-0.7%	-11
NOx	0	0
Polycyclics	-4.1%	
Weighted Toxins	-8.4%	

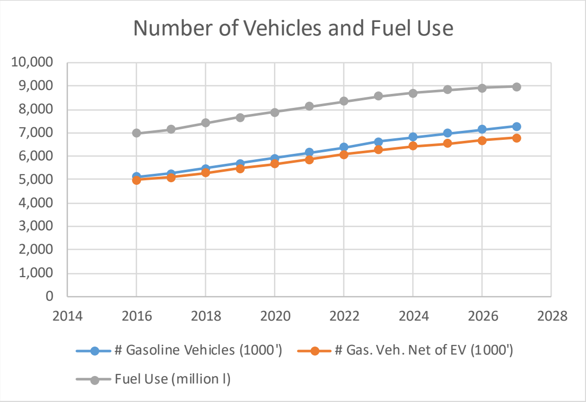
From Complex Model
Based on Fuel Samples

Toxic Air Contaminant	Relative Potency	Toxics Mass Change
benzene	0.17	-6.7%
acetaldehyde	0.02	154.7%
formaldehyde	0.04	-11.5%
1,3 butadiene	1.00	-10.4%
Polycyclics	0.00	-4.1%
Total Weighted:		-8.4%

iBEAM Output Mexico (E20

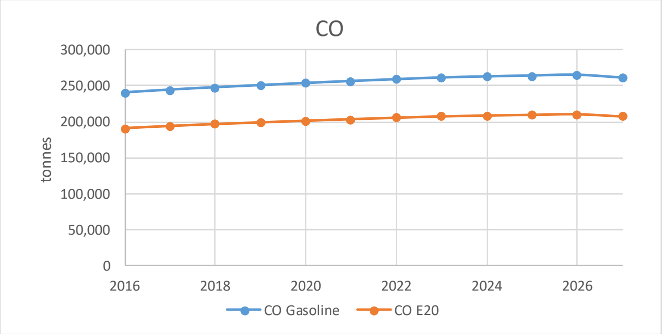
GDI Rate: 50% | **EV Rate: 7%**

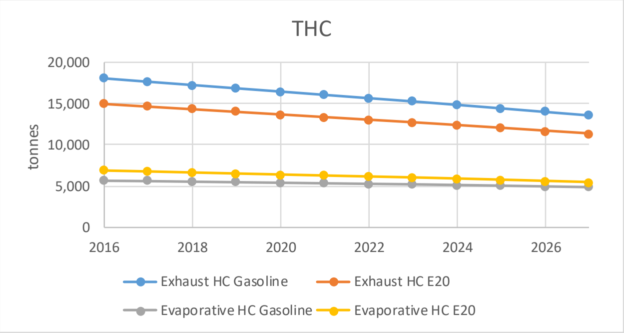
Year	# Gasoline Vehicles (1000')	# Gas. Veh. Net of EV (1000')	Fuel Use (million l)	FE (l/100 km)	VDT (million km/year)
2016	5,114	4,975	6,964	8.58	81,131
2017	5,268	5,104	7,153	8.51	84,014
2018	5,481	5,289	7,404	8.43	87,876
2019	5,698	5,477	7,650	8.33	91,840
2020	5,920	5,667	7,889	8.23	95,906
2021	6,151	5,864	8,123	8.11	100,142
2022	6,387	6,064	8,348	7.99	104,488
2023	6,628	6,267	8,561	7.86	108,948
2024	6,817	6,419	8,708	7.73	112,586
2025	6,988	6,553	8,824	7.61	115,934
2026	7,136	6,664	8,905	7.49	118,927
2027	7,288	6,777	8,974	7.36	121,993



tonnes

	CO		Exhaust HC		Evaporative HC		NOx		PM	
Year	Gasoline	E20	Gasoline	E20	Gasoline	E20	Gasoline	E20	Gasoline	E20
2016	240,214	190,784	18,071	15,024	5,699	6,932	52,726	52,726	127	125
2017	244,013	193,802	17,668	14,688	5,650	6,813	51,181	51,181	130	128
2018	247,398	196,490	17,276	14,362	5,579	6,675	49,515	49,515	134	131
2019	250,342	198,828	16,881	14,034	5,510	6,541	47,804	47,804	139	135
2020	253,349	201,216	16,494	13,712	5,442	6,409	46,096	46,096	143	139
2021	256,081	203,386	16,096	13,381	5,371	6,276	44,320	44,320	146	141
2022	258,641	205,420	15,702	13,054	5,304	6,149	42,578	42,578	148	142
2023	261,063	207,343	15,315	12,732	5,241	6,026	40,818	40,818	151	144
2024	262,551	208,525	14,903	12,390	5,158	5,882	39,030	39,030	153	145
2025	263,841	209,549	14,485	12,043	5,070	5,733	37,241	37,241	154	146
2026	264,842	210,344	14,058	11,687	4,974	5,573	35,452	35,452	155	146
2027	260,876	207,194	13,640	11,340	4,879	5,416	33,774	33,774	156	146
Total:	3,063,212	2,432,880	190,588	158,447	63,877	74,425	520,535	520,535	1,736	1,667
Savings		-630,332		-32,141		10,548		0		-69





	Relative to E0 (%)	Relative to E0 (Total Tonnes)
CO	-20.6%	-630,332
THC	-8.5%	-21,593
PM	-4.0%	-69
NOx	0	0
Polycyclics	-9.8%	
Weighted Toxins	-24.0%	

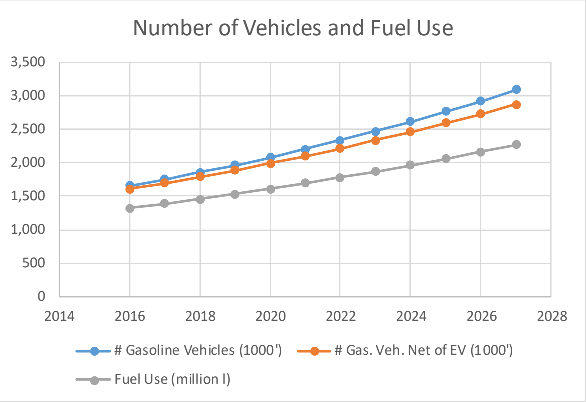
From Complex Model
Based on Fuel Samples

Toxic Air Contaminant	Relative Potency	Toxics Mass Change
benzene	0.17	-26.2%
acetaldehyde	0.02	522.2%
formaldehyde	0.04	-10.9%
1,3 butadiene	1.00	-27.8%
Polycyclics	0.00	-9.8%
Total Weighted:		-24.0%

iBEAM Output	New Del E10

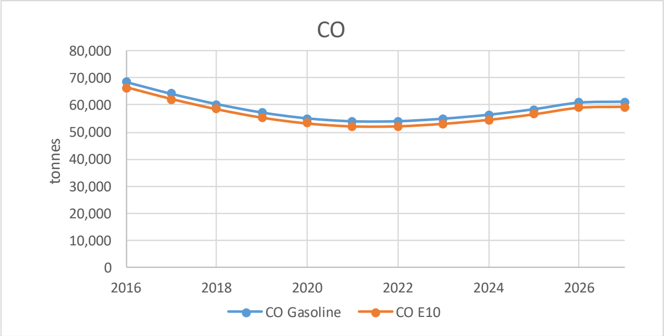
GDI Rate: 50%	EV Rate: 7%

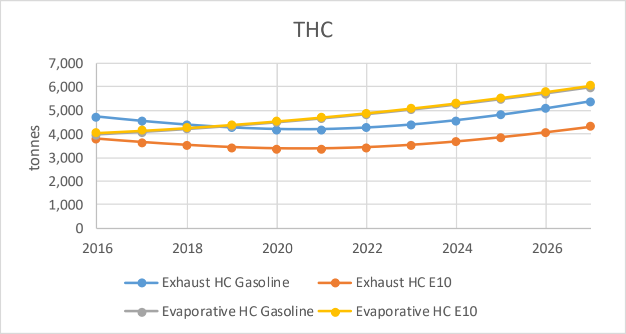
Year	# Gasoline Vehicles (1000')	# Gas. Veh. Net of EV (1000')	Fuel Use (million l)	FE (l/100 km)	VDT (million km/year)
2016	1,655	1,610	1,319	6.15	21,454
2017	1,753	1,699	1,388	6.07	22,848
2018	1,857	1,792	1,459	6.00	24,325
2019	1,967	1,890	1,533	5.92	25,891
2020	2,083	1,994	1,611	5.85	27,549
2021	2,205	2,102	1,692	5.77	29,304
2022	2,333	2,215	1,778	5.71	31,162
2023	2,469	2,335	1,869	5.64	33,127
2024	2,612	2,460	1,964	5.58	35,205
2025	2,763	2,591	2,063	5.52	37,401
2026	2,921	2,728	2,166	5.45	39,721
2027	3,088	2,872	2,273	5.39	42,171



tonnes

Year	CO		Exhaust HC		Evaporative HC		NOx		PM	
	Gasoline	E10	Gasoline	E10	Gasoline	E10	Gasoline	E10	Gasoline	E10
2016	68,694	66,568	4,726	3,804	3,980	4,068	4,997	4,997	34	33
2017	64,272	62,283	4,540	3,655	4,086	4,161	4,682	4,682	35	35
2018	60,427	58,557	4,385	3,529	4,208	4,276	4,417	4,417	36	36
2019	57,258	55,486	4,264	3,433	4,344	4,409	4,212	4,212	38	38
2020	55,067	53,362	4,197	3,379	4,494	4,558	4,028	4,028	40	39
2021	53,969	52,298	4,195	3,377	4,659	4,723	3,928	3,928	40	40
2022	53,997	52,325	4,261	3,430	4,839	4,904	3,908	3,908	41	41
2023	54,935	53,235	4,389	3,533	5,036	5,102	3,951	3,951	42	42
2024	56,414	54,668	4,574	3,682	5,249	5,318	4,044	4,044	43	43
2025	58,479	56,669	4,807	3,869	5,479	5,550	4,172	4,172	44	44
2026	60,962	59,075	5,078	4,088	5,726	5,800	4,322	4,322	46	45
2027	61,324	59,426	5,378	4,329	5,991	6,068	4,482	4,482	47	46
Total:	705,798	683,953	54,795	44,108	58,092	58,937	51,142	51,142	486	480
Savings		-21,844		-10,687		845		0		-6





	Relative to E0 (%)	Relative to E0 (Total Tonnes)
CO	-3.1%	-21,844
THC	-8.7%	-9,842
PM	-1.2%	-6
NOx	0	0
Polycyclics	-6.6%	
Weighted Toxins	-21.2%	

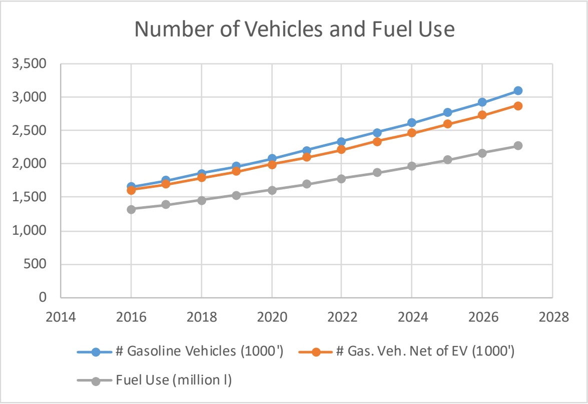
From Complex Model
Based on Fuel Samples

Toxic Air Contaminant	Relative Potency	Toxics Mass Change
benzene	0.17	-21.6%
acetaldehyde	0.02	153.0%
formaldehyde	0.04	-1.5%
1,3 butadiene	1.00	-22.5%
Polycyclics	0.00	-6.6%
Total Weighted:		-21.2%

iBEAM Output New Del E20

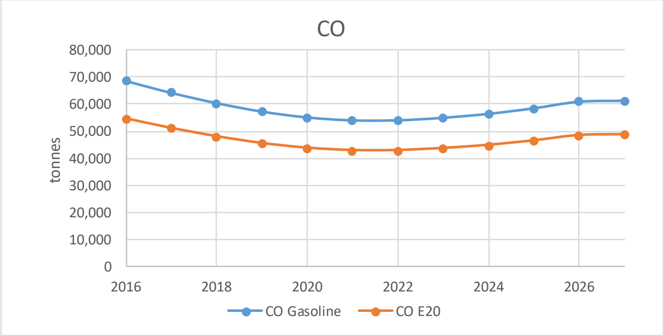
GDI Rate: 50% **EV Rate: 7%**

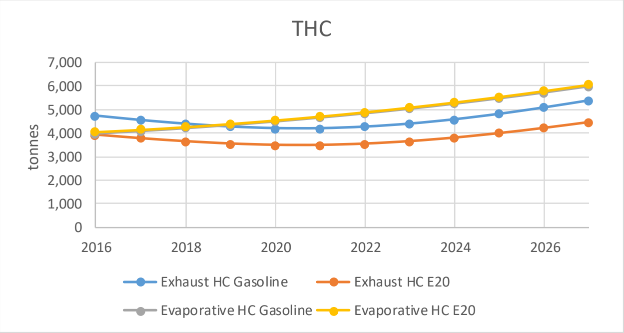
Year	# Gasoline Vehicles (1000')	# Gas. Veh. Net of EV (1000')	Fuel Use (million l)	FE (l/100 km)	VDT (million km/year)
2016	1,655	1,610	1,319	6.15	21,454
2017	1,753	1,699	1,388	6.07	22,848
2018	1,857	1,792	1,459	6.00	24,325
2019	1,967	1,890	1,533	5.92	25,891
2020	2,083	1,994	1,611	5.85	27,549
2021	2,205	2,102	1,692	5.77	29,304
2022	2,333	2,215	1,778	5.71	31,162
2023	2,469	2,335	1,869	5.64	33,127
2024	2,612	2,460	1,964	5.58	35,205
2025	2,763	2,591	2,063	5.52	37,401
2026	2,921	2,728	2,166	5.45	39,721
2027	3,088	2,872	2,273	5.39	42,171


Number of Vehicles and Fuel Use

tonnes

Year	CO		Exhaust HC		Evaporative HC		NOx		PM	
	Gasoline	E20	Gasoline	E20	Gasoline	E20	Gasoline	E20	Gasoline	E20
2016	68,694	54,559	4,726	3,933	3,980	4,068	4,997	4,997	34	33
2017	64,272	51,047	4,540	3,778	4,086	4,161	4,682	4,682	35	34
2018	60,427	47,993	4,385	3,649	4,208	4,276	4,417	4,417	36	35
2019	57,258	45,476	4,264	3,549	4,344	4,409	4,212	4,212	38	36
2020	55,067	43,735	4,197	3,493	4,494	4,558	4,028	4,028	40	37
2021	53,969	42,863	4,195	3,491	4,659	4,723	3,928	3,928	40	38
2022	53,997	42,885	4,261	3,546	4,839	4,904	3,908	3,908	41	38
2023	54,935	43,631	4,389	3,653	5,036	5,102	3,951	3,951	42	39
2024	56,414	44,805	4,574	3,806	5,249	5,318	4,044	4,044	43	39
2025	58,479	46,446	4,807	4,000	5,479	5,550	4,172	4,172	44	40
2026	60,962	48,418	5,078	4,226	5,726	5,800	4,322	4,322	46	41
2027	61,324	48,705	5,378	4,475	5,991	6,068	4,482	4,482	47	41
Total:	705,798	560,562	54,795	45,597	58,092	58,937	51,142	51,142	486	451
Savings		-145,236		-9,198		845		0		-35


CO


THC

	Relative to E0 (%)	Relative to E0 (Total Tonnes)
CO	-20.6%	-145,236
THC	-7.4%	-8,353
PM	-7.1%	-35
NOx	0	0
Polycyclics	-9.4%	
Weighted Toxins	-36.6%	

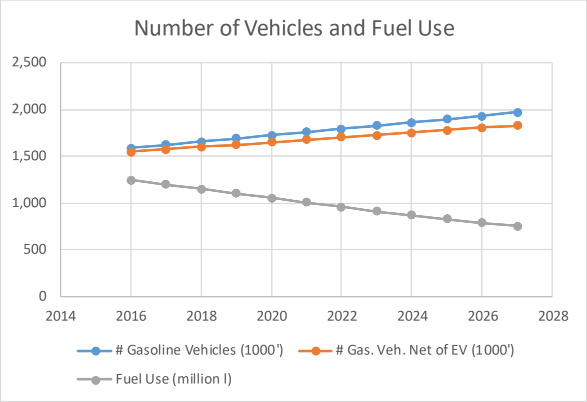
From Complex Model
Based on Fuel Samples

Toxic Air Contaminant	Relative Potency	Toxics Mass Change
benzene	0.17	-40.7%
acetaldehyde	0.02	549.3%
formaldehyde	0.04	2.5%
1,3 butadiene	1.00	-38.7%
Polycyclics	0.00	-9.4%
Total Weighted:		-36.6%

iBEAM Output Seoul E10

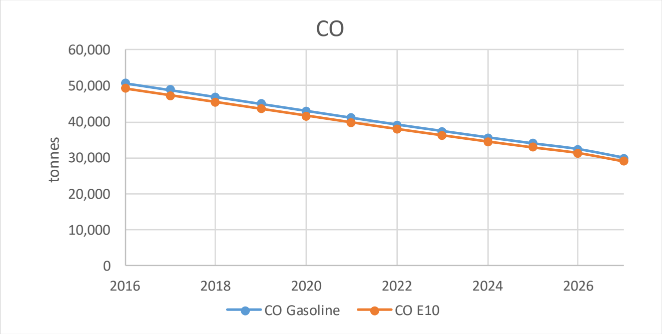
GDI Rate: 50% **EV Rate: 7%**

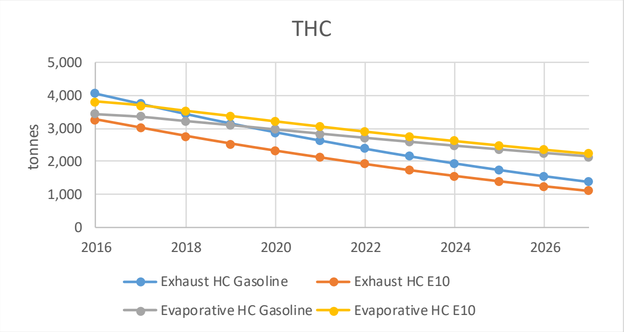
Year	# Gasoline Vehicles (1000')	# Gas. Veh. Net of EV (1000')	Fuel Use (million l)	FE (l/100 km)	VDT (million km/year)
2016	1,590	1,546	1,248	7.82	15,967
2017	1,622	1,572	1,200	7.66	15,664
2018	1,655	1,597	1,151	7.49	15,367
2019	1,689	1,623	1,102	7.31	15,076
2020	1,722	1,648	1,051	7.11	14,790
2021	1,756	1,674	1,003	6.91	14,509
2022	1,791	1,700	957	6.72	14,233
2023	1,826	1,726	912	6.53	13,962
2024	1,861	1,752	869	6.35	13,696
2025	1,896	1,778	828	6.16	13,435
2026	1,931	1,803	789	5.99	13,178
2027	1,967	1,829	751	5.81	12,927



tonnes

Year	CO		Exhaust HC		Evaporative HC		NOx		PM	
	Gasoline	E10	Gasoline	E10	Gasoline	E10	Gasoline	E10	Gasoline	E10
2016	50,803	49,231	4,055	3,262	3,448	3,814	4,981	4,981	25	25
2017	48,880	47,367	3,746	3,014	3,367	3,696	4,629	4,629	24	24
2018	46,964	45,510	3,440	2,767	3,236	3,532	4,278	4,278	24	23
2019	45,024	43,631	3,153	2,536	3,112	3,376	3,947	3,947	23	23
2020	43,091	41,758	2,885	2,321	2,977	3,213	3,633	3,633	22	22
2021	41,160	39,886	2,632	2,118	2,848	3,057	3,364	3,364	21	21
2022	39,267	38,052	2,385	1,918	2,719	2,904	3,076	3,076	21	20
2023	37,463	36,304	2,153	1,732	2,595	2,758	2,803	2,803	20	20
2024	35,693	34,589	1,938	1,559	2,476	2,619	2,551	2,551	19	19
2025	34,003	32,951	1,738	1,398	2,361	2,485	2,317	2,317	18	18
2026	32,396	31,393	1,551	1,247	2,251	2,357	2,099	2,099	18	17
2027	30,028	29,098	1,376	1,107	2,144	2,234	1,850	1,850	17	17
Total:	484,773	469,769	31,052	24,979	33,534	36,045	39,529	39,529	251	249
Savings		-15,004		-6,073		2,510		0		-1





	Relative to E0 (%)	Relative to E0 (Total Tonnes)
CO	-3.1%	-15,004
THC	-5.5%	-3,562
PM	-0.6%	-1
NOx	0	0
Polycyclics	-7.0%	
Weighted Toxins	-19.8%	

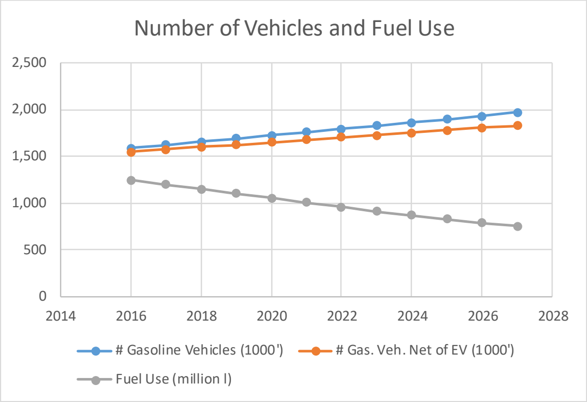
From Complex Model
Based on Fuel Samples

Toxic Air Contaminant	Relative Potency	Toxics Mass Change
benzene	0.17	-21.2%
acetaldehyde	0.02	143.6%
formaldehyde	0.04	3.3%
1,3 butadiene	1.00	-21.1%
Polycyclics	0.00	-7.0%
Total Weighted:		-19.8%

iBEAM Output Seoul E20

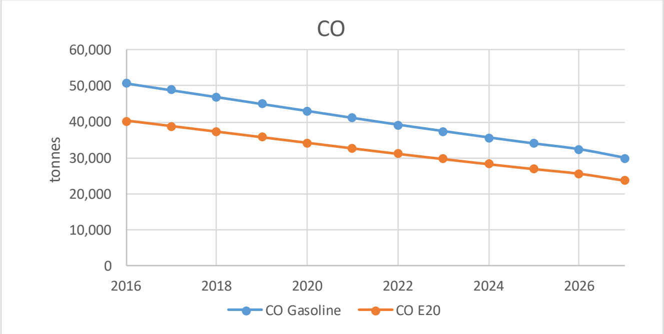
GDI Rate: 50% **EV Rate: 7%**

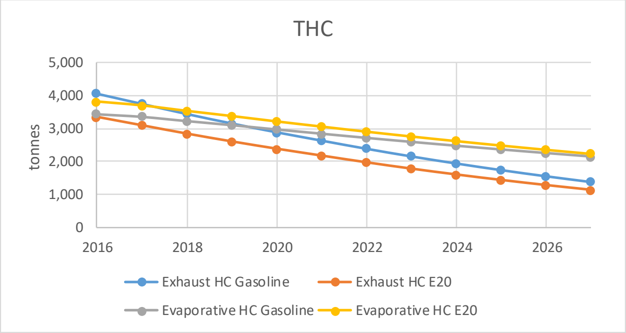
Year	# Gasoline Vehicles (1000')	# Gas. Veh. Net of EV (1000')	Fuel Use (million l)	FE (l/100 km)	VDT (million km/year)
2016	1,590	1,546	1,248	7.82	15,967
2017	1,622	1,572	1,200	7.66	15,664
2018	1,655	1,597	1,151	7.49	15,367
2019	1,689	1,623	1,102	7.31	15,076
2020	1,722	1,648	1,051	7.11	14,790
2021	1,756	1,674	1,003	6.91	14,509
2022	1,791	1,700	957	6.72	14,233
2023	1,826	1,726	912	6.53	13,962
2024	1,861	1,752	869	6.35	13,696
2025	1,896	1,778	828	6.16	13,435
2026	1,931	1,803	789	5.99	13,178
2027	1,967	1,829	751	5.81	12,927



tonnes

Year	CO		Exhaust HC		Evaporative HC		NOx		PM	
	Gasoline	E20	Gasoline	E20	Gasoline	E20	Gasoline	E20	Gasoline	E20
2016	50,803	40,349	4,055	3,339	3,448	3,814	4,981	4,981	25	25
2017	48,880	38,822	3,746	3,085	3,367	3,696	4,629	4,629	24	24
2018	46,964	37,300	3,440	2,833	3,236	3,532	4,278	4,278	24	23
2019	45,024	35,759	3,153	2,597	3,112	3,376	3,947	3,947	23	22
2020	43,091	34,224	2,885	2,376	2,977	3,213	3,633	3,633	22	22
2021	41,160	32,690	2,632	2,168	2,848	3,057	3,364	3,364	21	21
2022	39,267	31,187	2,385	1,964	2,719	2,904	3,076	3,076	21	20
2023	37,463	29,754	2,153	1,773	2,595	2,758	2,803	2,803	20	19
2024	35,693	28,349	1,938	1,596	2,476	2,619	2,551	2,551	19	18
2025	34,003	27,006	1,738	1,431	2,361	2,485	2,317	2,317	18	17
2026	32,396	25,730	1,551	1,277	2,251	2,357	2,099	2,099	18	17
2027	30,028	23,849	1,376	1,133	2,144	2,234	1,850	1,850	17	16
Total:	484,773	385,019	31,052	25,574	33,534	36,045	39,529	39,529	251	242
Savings		-99,754		-5,478		2,510		0		-8





	Relative to E0 (%)	Relative to E0 (Total Tonnes)
CO	-20.6%	-99,754
THC	-4.6%	-2,968
PM	-3.4%	-8
NOx	0	0
Polycyclics	-13.7%	
Weighted Toxins	-36.3%	

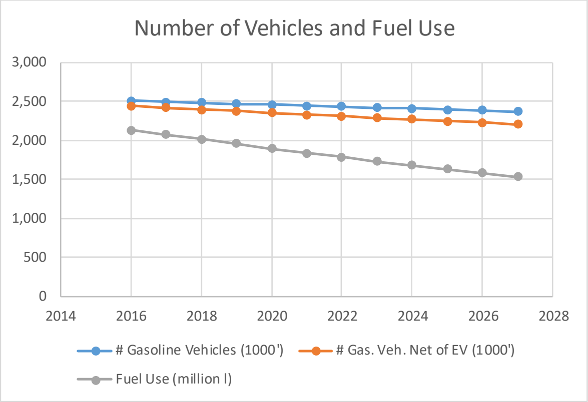
From Complex Model
Based on Fuel Samples

Toxic Air Contaminant	Relative Potency	Toxics Mass Change
benzene	0.17	-33.6%
acetaldehyde	0.02	465.9%
formaldehyde	0.04	-1.2%
1,3 butadiene	1.00	-41.2%
Polycyclics	0.00	-13.7%
Total Weighted:		-36.3%

iBEAM Output Tokyo E10

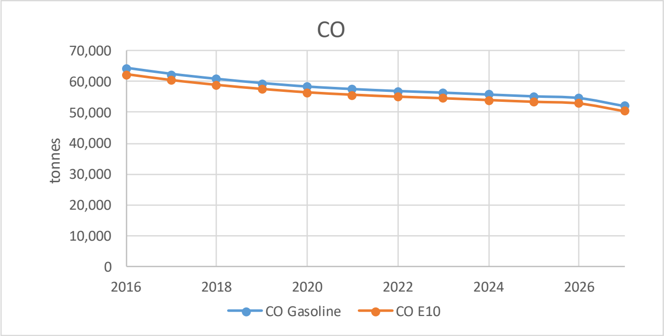
GDI Rate: 50% **EV Rate: 7%**

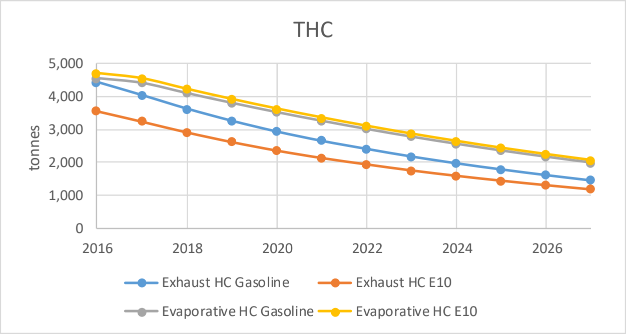
Year	# Gasoline Vehicles (1000')	# Gas. Veh. Net of EV (1000')	Fuel Use (million l)	FE (l/100 km)	VDT (million km/year)
2016	2,510	2,442	2,136	6.89	31,013
2017	2,498	2,420	2,078	6.76	30,744
2018	2,485	2,398	2,018	6.62	30,481
2019	2,473	2,377	1,958	6.48	30,224
2020	2,460	2,355	1,897	6.33	29,972
2021	2,448	2,334	1,842	6.18	29,784
2022	2,436	2,313	1,787	6.04	29,599
2023	2,424	2,292	1,735	5.90	29,418
2024	2,412	2,271	1,683	5.75	29,241
2025	2,399	2,250	1,632	5.61	29,068
2026	2,387	2,230	1,583	5.48	28,916
2027	2,376	2,209	1,535	5.34	28,768


Number of Vehicles and Fuel Use

tonnes

Year	CO		Exhaust HC		Evaporative HC		NOx		PM	
	Gasoline	E10	Gasoline	E10	Gasoline	E10	Gasoline	E10	Gasoline	E10
2016	64,294	62,305	4,424	3,562	4,552	4,698	5,029	5,029	48	48
2017	62,360	60,430	4,029	3,244	4,407	4,539	4,632	4,632	47	47
2018	60,786	58,904	3,622	2,916	4,097	4,217	4,275	4,275	46	46
2019	59,457	57,617	3,258	2,623	3,801	3,911	3,958	3,958	45	45
2020	58,343	56,537	2,935	2,363	3,520	3,622	3,684	3,684	44	44
2021	57,550	55,769	2,656	2,138	3,258	3,353	3,472	3,472	43	43
2022	56,918	55,156	2,414	1,943	3,010	3,099	3,285	3,285	42	41
2023	56,409	54,663	2,185	1,759	2,777	2,861	3,129	3,129	40	40
2024	55,808	54,081	1,981	1,595	2,561	2,641	3,002	3,002	39	39
2025	55,237	53,527	1,797	1,447	2,357	2,433	2,898	2,898	38	37
2026	54,689	52,996	1,626	1,309	2,169	2,241	2,741	2,741	37	36
2027	52,166	50,551	1,467	1,181	1,992	2,061	2,562	2,562	35	35
Total:	694,017	672,537	32,394	26,078	38,499	39,678	42,668	42,668	506	502
Savings		-21,480		-6,316		1,179		0		-4


CO


THC

	Relative to E0 (%)	Relative to E0 (Total Tonnes)
CO	-3.1%	-21,480
THC	-7.2%	-5,137
PM	-0.8%	-4
NOx	0	0
Polycyclics	-6.5%	
Weighted Toxins	-14.7%	

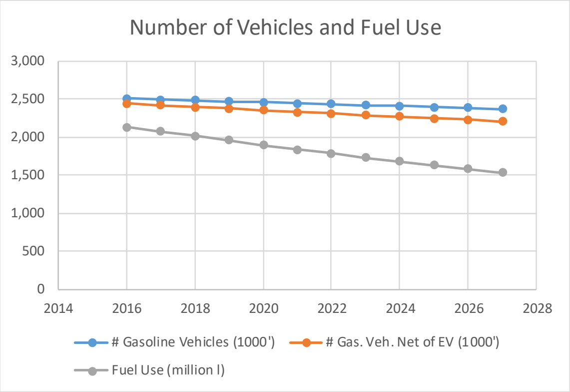
From Complex Model
Based on Fuel Samples

Toxic Air Contaminant	Relative Potency	Toxics Mass Change
benzene	0.17	-14.6%
acetaldehyde	0.02	76.4%
formaldehyde	0.04	0.2%
1,3 butadiene	1.00	-15.8%
Polycyclics	0.00	-6.5%
Total Weighted:		-14.7%

iBEAM Output Tokyo E20

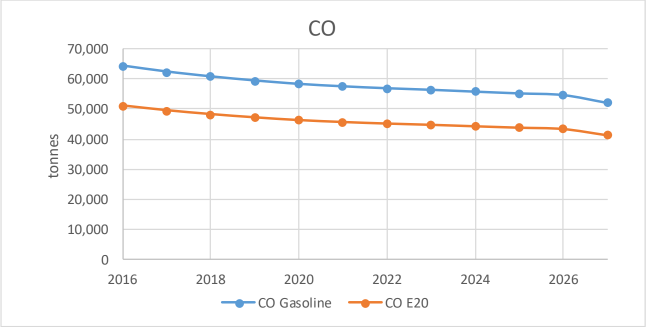
GDI Rate: 50% EV Rate: 7%

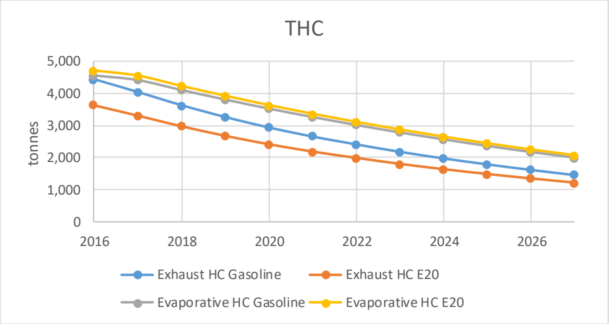
Year	# Gasoline Vehicles (1000')	# Gas. Veh. Net of EV (1000')	Fuel Use (million l)	FE (l/100 km)	VDT (million km/year)
2016	2,510	2,442	2,136	6.89	31,013
2017	2,498	2,420	2,078	6.76	30,744
2018	2,485	2,398	2,018	6.62	30,481
2019	2,473	2,377	1,958	6.48	30,224
2020	2,460	2,355	1,897	6.33	29,972
2021	2,448	2,334	1,842	6.18	29,784
2022	2,436	2,313	1,787	6.04	29,599
2023	2,424	2,292	1,735	5.90	29,418
2024	2,412	2,271	1,683	5.75	29,241
2025	2,399	2,250	1,632	5.61	29,068
2026	2,387	2,230	1,583	5.48	28,916
2027	2,376	2,209	1,535	5.34	28,768



tonnes

	CO		Exhaust HC		Evaporative HC		NOx		PM	
Year	Gasoline	E20	Gasoline	E20	Gasoline	E20	Gasoline	E20	Gasoline	E20
2016	64,294	51,064	4,424	3,637	4,552	4,698	5,029	5,029	48	48
2017	62,360	49,528	4,029	3,313	4,407	4,539	4,632	4,632	47	46
2018	60,786	48,278	3,622	2,978	4,097	4,217	4,275	4,275	46	45
2019	59,457	47,222	3,258	2,679	3,801	3,911	3,958	3,958	45	44
2020	58,343	46,337	2,935	2,413	3,520	3,622	3,684	3,684	44	43
2021	57,550	45,708	2,656	2,183	3,258	3,353	3,472	3,472	43	41
2022	56,918	45,206	2,414	1,984	3,010	3,099	3,285	3,285	42	40
2023	56,409	44,802	2,185	1,796	2,777	2,861	3,129	3,129	40	38
2024	55,808	44,324	1,981	1,629	2,561	2,641	3,002	3,002	39	37
2025	55,237	43,871	1,797	1,478	2,357	2,433	2,898	2,898	38	35
2026	54,689	43,435	1,626	1,337	2,169	2,241	2,741	2,741	37	34
2027	52,166	41,431	1,467	1,206	1,992	2,061	2,562	2,562	35	32
Total:	694,017	551,206	32,394	26,634	38,499	39,678	42,668	42,668	506	483
Savings		-142,811		-5,760		1,179		0		-23





	Relative to E0 (%)	Relative to E0 (Total Tonnes)
CO	-20.6%	-142,811
THC	-6.5%	-4,581
PM	-4.6%	-23
NOx	0	0
Polycyclics	-14.4%	
Weighted Toxins	-32.1%	

From Complex Model Based on Fuel Samples

Toxic Air Contaminant	Relative Potency	Toxics Mass Change
benzene	0.17	-32.1%
acetaldehyde	0.02	323.3%
formaldehyde	0.04	1.2%
1,3 butadiene	1.00	-35.7%
Polycyclics	0.00	-14.4%
Total Weighted:		-32.1%

Figure 17: Individual Emissions Results By City and Ethanol Blend

11 GHG Life Cycle Emissions Savings from E10 and E20 Blends

In this section we assess the greenhouse gas emissions on a life cycle basis for ethanol produced and shipped from the United States to each of the five studied cities and blended on location into E10 and E20 gasolines. These emissions are then compared to current gasolines produced in the countries.

The GHG spreadsheet in iBEAM calculates the GHG emissions based on data from two life cycle models:

1) The GREET model developed by Argonne National Laboratory which is the gold standard for U.S. based life cycle analysis and contains the most up to date information on corn ethanol production. A California version of the GREET model is used for the Low Carbon Fuel Standard. An earlier version was used by the US Environmental Protection Agency for the Renewable Fuel Standard modeling.
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 along both the GREET and the Biograce model stems from the fact that the GHG Emissions for gasoline in the Biograce model is based on a study by the European Joint Research Center (JRC) which results in much lower values than those for GREET due to several reasons. The JRC analysis initially relied on a simpler assessment of crude oil production which alone accounted for 4 grams carbon dioxide per megajoule (gCO2e/MJ) difference from the GREET estimates. Also, the JRC analysis examined the incremental effect of producing gasoline from an oil refinery that is heavily configured for diesel production. Finally, the JRC study looked at incremental gasoline production for a European refinery showing efficiency gains for incremental volumes. In contrast the refinery analysis for the GREET model examined the configurations of US refineries and assigned emissions to the average gallon of gasoline produced.

11.1 GHG Emissions of US Produced Ethanol Shipped to Each City

The iBEAM model displays the energy inputs and emissions from corn ethanol over the life cycle from farming to end use. The carbon in the corn is treated as biogenic carbon neutral and the approach follows the methods for ANL's GREET model. Emissions for the farming step include farming energy, fertilizer inputs, N_2O emission from nitrogen fertilizer and crop residue and corn transport. The ethanol plant produces ethanol and dried distillers grains (DGS). A coproduct credit for DGS is calculated based on its value as animal feed. Ethanol plant emissions include emissions from natural gas, electric power and chemicals and enzymes.

The figure below shows the system boundary diagram for the ethanol pathway. Three analysis approaches are configured into iBEAM.

1) The first analysis approach is based on the GREET_2017 model with a substitution credit for the animal feed coproduced at the ethanol plant. In the substitution approach the main product (ethanol) receives a GHG emissions credit based on the life cycle emissions of the products displaced by the animal feed coproduction (DGS). In this case the displaced products are corn, soybean meal, and urea.
2) The second analysis approach utilizes GREET data with energy allocation. With the energy allocation approach, the total life cycle emissions are distributed based on an allocation factor.

The allocation is based on the energy content of ethanol vs. the total energy content of all products produced at the ethanol plant (ethanol+DGS).

3) The third analysis approach utilizes the BioGrace model with energy allocation. Since the EU certification approach requires energy allocation of emissions this calculation method was incorporated into iBEAM.

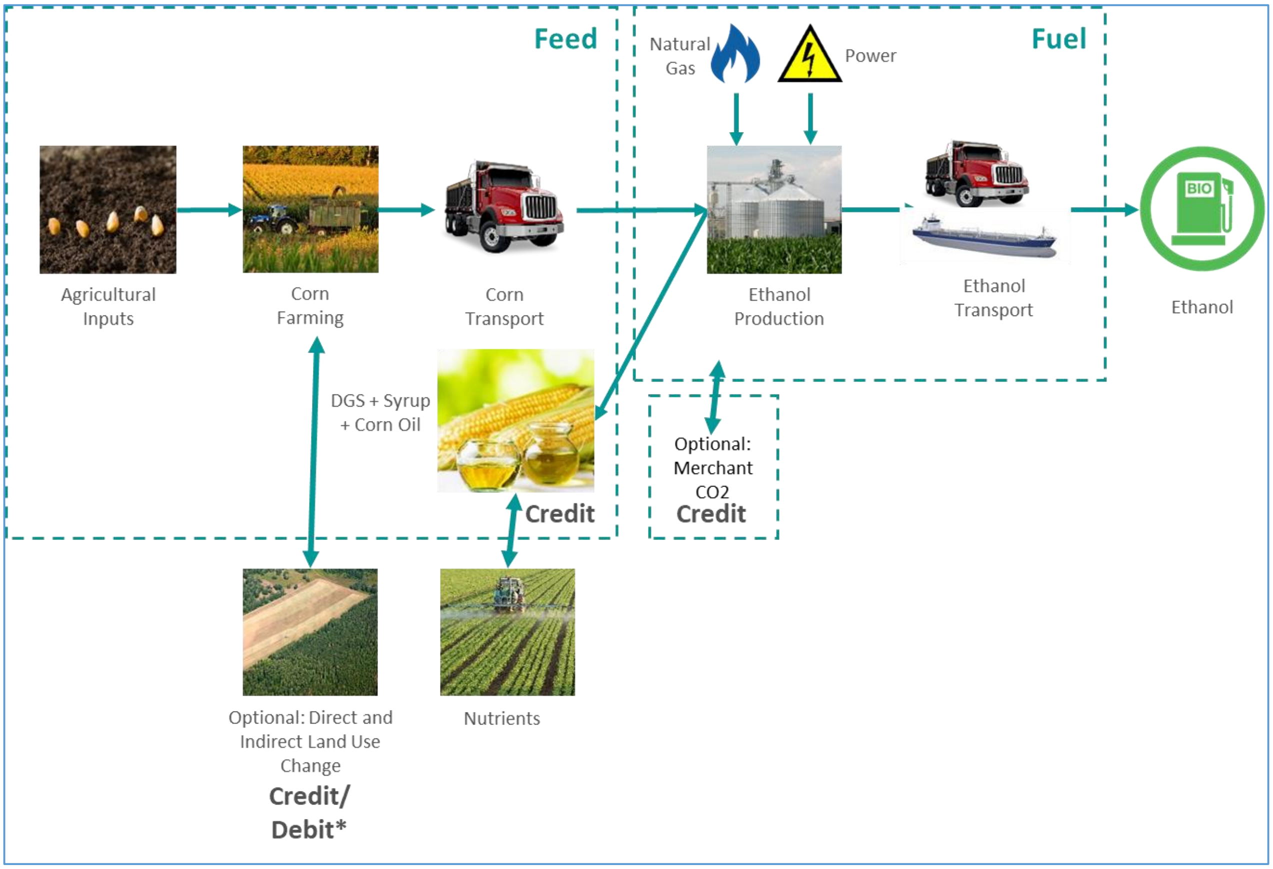


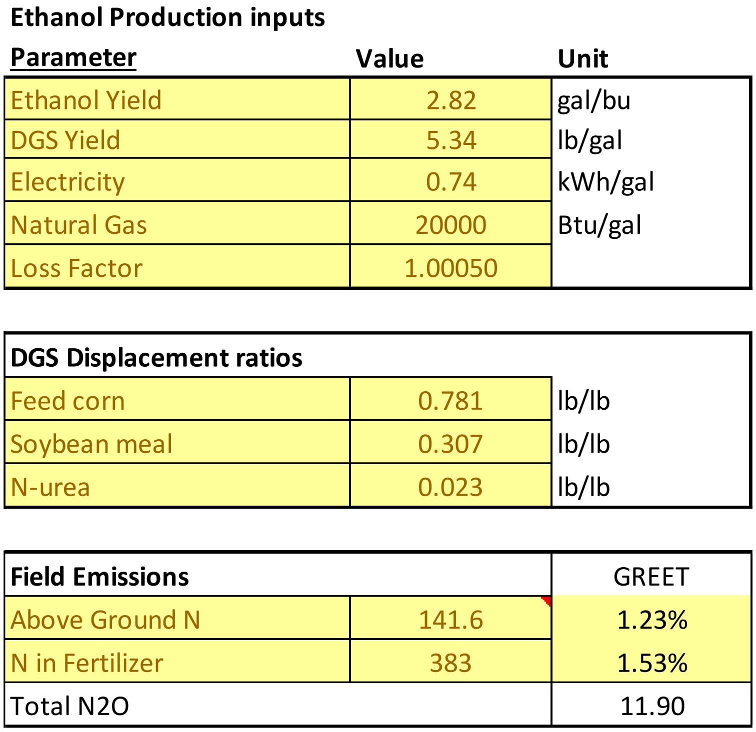
Figure 18: System Boundary Diagram for Corn Ethanol Production

The table below shows the inputs to the iBEAM model.

- The ethanol plant input parameters determine the life cycle GHG emissions for that production step. The DGS displacement ratios produce a GHG emissions credit in the ethanol pathway for the animal food coproduced at ethanol plants.
- Nitrogen emissions from fertilizer application are a large contributor to the ethanol life cycle GHG emissions.
- The energy intensity values for transportation differ between GREET and Biograce and both sets of assumptions are shown.
- Emissions from Indirect Land Use Change (iLUC) are not considered in this analysis which is consistent with the current practice under the EU and Japanese guidelines.
- Emissions credits from Direct Land Use change are considered in the Biograce modeling approach. This is consistent with the RED modeling approach which allows for emissions savings from agriculture based on improved management practices (see Appendix C).

- iBEAM has an option to consider a coproduct GHG credit for ethanol plants that recover CO_2 for sale into the merchant gas markets (beverage CO_2, food processing). Under certain conditions ethanol for certification into the EU markets under the RED can claim a coproduct credit for CO_2 recovery (see Appendix C and Case Study Sweden http://www.iscc-system.org/en/iscc-system/iscc-trailer/)
- The transportation distances were changed to reflect the GHG emissions incurred during shipment to the target cities (see table below)

Table 24: Inputs for GHG Emissions Assessments in iBEAM

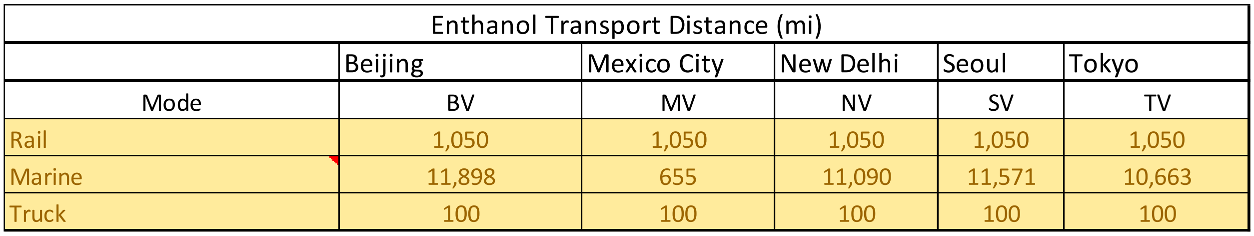


Ethanol Production inputs

Parameter	Value	Unit
Ethanol Yield	2.82	gal/bu
DGS Yield	5.34	lb/gal
Electricity	0.74	kWh/gal
Natural Gas	20000	Btu/gal
Loss Factor	1.00050	

DGS Displacement ratios		
Feed corn	0.781	lb/lb
Soybean meal	0.307	lb/lb
N-urea	0.023	lb/lb

Field Emissions		GREET
Above Ground N	141.6	1.23%
N in Fertilizer	383	1.53%
Total N2O		11.90



Enthanol Transport Distance (mi)

	Beijing	Mexico City	New Delhi	Seoul	Tokyo
Mode	BV	MV	NV	SV	TV
Rail	1,050	1,050	1,050	1,050	1,050
Marine	11,898	655	11,090	11,571	10,663
Truck	100	100	100	100	100

The table below shows the GHG modeling results from the different models (GREET, Biograce) and the different coproduct allocation approaches (substitution, energy allocation).

Table 25: GHG Example Calculations for Tokyo

Carbon Intensity Calculations

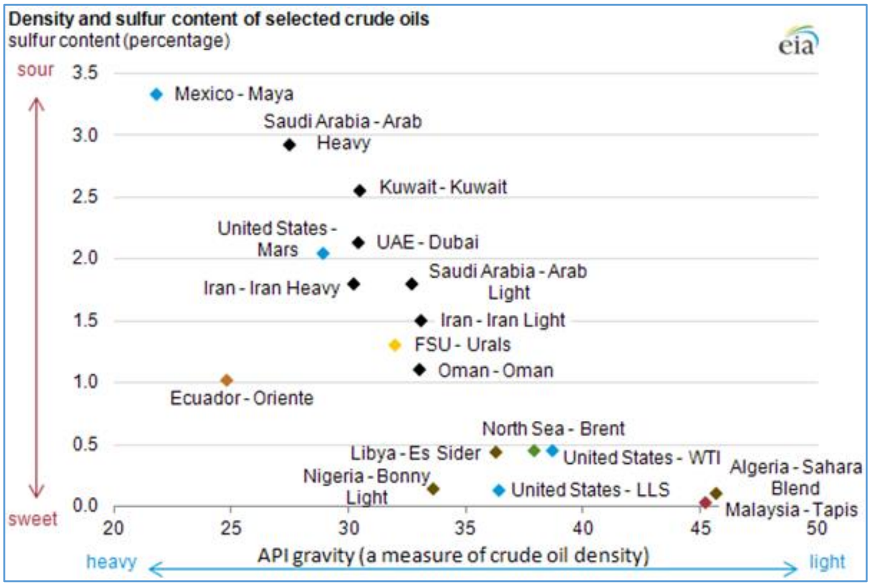
			GREET					**JRC EU**			
					CI (g CO$_2$e/MJ)		**kg CO$_2$/bu**			**CI (g CO$_2$e/MJ)**	
EtOH production step	**Use Rate**	**Unit**	**LCI Data**	**Unit**	**Substitution**	**Allocation**		**LCI Data**	**Unit**	**Unallocated**	**Allocation**
Direct Land Use				g CO$_2$e/MJ				-3.8	g CO$_2$e/MJ		-3.77
Corn Farming	7.31	MJ/bu	92.1	g CO$_2$e/MJ	2.97	1.93	0.67	87.6	g CO$_2$e/MJ	2.82	1.84
CO2 emissions from urea	348	g/bu	1.0	g CO$_2$e/g	1.53	1.00	0.35	1	g CO$_2$e/g	1.53	1.00
Nitrogen Fertilizer	383	g/bu	3.86	g CO$_2$e/g	6.52	4.25	1.48	3.86	g CO$_2$e/g	6.52	4.25
Field N2O from fertilizer			0.12	g CO$_2$e/g corn	13.90	9.05	3.16	0.13	g CO$_2$e/g corn	14.75	9.61
P2O5	139	g/bu	1.46	g CO$_2$e/g	0.89	0.58	0.20	1.01	g CO$_2$e/g	0.620	0.40
K2O	146	g/bu	0.61	g CO$_2$e/g	0.39	0.25	0.09	0.58	g CO$_2$e/g	0.372	0.24
CaCO3	1290	g/bu	0.01	g CO$_2$e/g	0.06	0.04	0.01	0.13	g CO$_2$e/g	0.736	0.48
Field CO2 from CaCO3	279	g/bu	1	g CO$_2$e/g	1.23	0.80	0.28		g CO$_2$e/g		
Herbicide	5.85	g/bu	19.95	g CO$_2$e/g	0.51	0.34	0.12	10.97	g CO$_2$e/g	0.283	0.18
Insecticide	0.01	g/bu	22.99	g CO$_2$e/g	0.001	0.00	0.00		g CO$_2$e/g		
Corn Transport	10	MHDDT mi	93.04	g CO$_2$e/MJ	0.47	0.31	0.11	87.64	g CO$_2$e/MJ	0.46	0.30
	40	HHDDT mi	94.04	g CO$_2$e/MJ	1.15	0.75	0.26		g CO$_2$e/MJ		
Corn Production					*29.62*	*19.30*	*6.73*			*28.10*	*18.31*
Displaced Corn	-4.17		0.26	g CO$_2$e/g corn	-6.22						
Displaced Soybean Meal	-1.64		0.49	g CO$_2$e/g SBM	-4.52						
Displaced Urea	-0.12		1.27	g CO$_2$e/g Urea	-0.8658						
Enteric CH$_4$			-2.14	g CO2e/MJ EtOH	-2.14	-1.40				-2.14	-1.40
CO$_2$ Bottling	0.00		37.40	g CO$_2$e/MJ	0.00	0.00					
NG Boiler	21.10	MJ/gal	69.54	g CO$_2$e/MJ	18.23	11.88		67.59	g CO$_2$e/MJ	17.72	11.54
Electric Power	2.66	MJ/gal	150.96	g CO$_2$e/MJ	5.00	3.26		150.96	g CO$_2$e/MJ	5.00	3.26
Enzymes & Chemicals			1.96	g CO$_2$e/MJ	1.96	1.28			g CO$_2$e/MJ	1.96	1.28
Ethanol Transport											
	1,050	Rail mi	93.21	g CO$_2$e/MJ	1.16	1.16		127.65	g CO$_2$e/MJ		1.04
	10,663	Marine mi	96.12	g CO$_2$e/MJ	6.40	6.40		87.20	g CO$_2$e/MJ		7.02
	100	Truck mi	93.04	g CO$_2$e/MJ	0.57	0.57		87.64	g CO$_2$e/MJ		0.33
Feed Phase					*15.88*	*17.90*					*16.91*
Fuel Phase					*33.31*	*24.54*					*24.47*
Indirect Land Use					*7.84*	*5.11*					
Total Without ILUC					**49.19**	**47.55**					**41.38**
Total With ILUC					57.03	52.66					

Note: no merchant CO$_2$ credit applied

11.2 GHG Emissions of the Gasoline Baselines in Each City

The GHG emissions from ethanol are compared with the gasoline/oxygenate blends that are available in each of the five cities. The GHG emissions of petroleum gasoline and MTBE is determined in the GREET model. The Japan Research Institute (JRI) estimated the GHG emissions of its current ETBE supply which is incorporated in our modeling effort.

GREET estimates the emissions from crude oil to gasoline based on the complexity of the oil refineries in different regions of the U.S. Among other parameters the GHG emissions from a refinery are directly related to the density of crude oils measured in API gravity. Crude oils that are light (higher degrees of API gravity or lower density) tend to require less intensive processing which results in lower GHG emissions. However, most of the refineries examined in this study, except for New Delhi, have complex cracking and conversion units that are comparable to refineries in the U.S. The figure below shows the API gravity for different crude oils by origin.



Source: https://www.eia.gov/todayinenergy/detail.php?id=7110

Figure 19: API Gravity for Major Oil Fields

The API gravity for the crude oil processed in each of our 5 countries of interest was calculated based on the published weighted average mix of crude oil imports from different global fields (http://www.worldstopexports.com/crude-oil-imports-by-country/). The table below shows that while the API for major global fields differs significantly the weighted average API values for each of our countries of interest are actually quite similar. We parameterized GREET with the respective weighted average API.

Table 26: API Gravity for Crude Oil Imported into Each of the 5 Countries of Interest

Source	**API**	**China**	**India**	**Japan**	**Mexico (US Mix)***	**South Korea**
Algeria	45.8				0.9296	0
Ecuador	24.9			0.209	3.6	0
Iran	31.9	9.5	6.7	3.3		5
Kuwait	30.5	4.8	2.7	3.1	3.3	16
Libya	36.4					0
Malaysia	45.2		1.7	0.279		0
Mexico	22.0		1.5	1.3	7.8	0
Nigeria	33.8		6.6		3.8	0
North Sea	38.0	1.7				0
Oman	33.6	11.1		0.642		0
Russia	32.0	16.8		3.3	0.686	4
Saudi Arabia	30.4	15.6	12.1	18	16.6	34
UAE	30.3	3.9	5.6	12.9		12
United States	35.0					0
Average API		**31.80**	**31.60**	**30.46**	**28.83**	**30.58**

* Note: Mexico produced crude oil that is exported and imports gasoline and crude oil from the U.S.

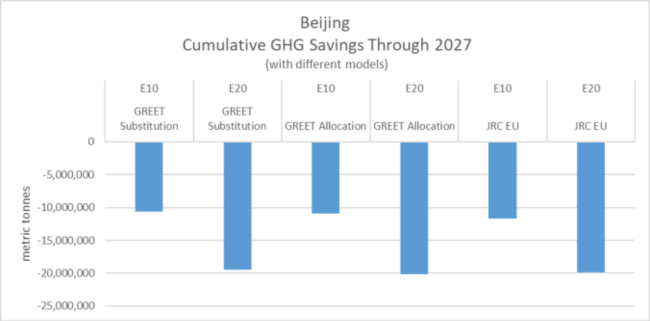
11.3 GHG Modeling Results

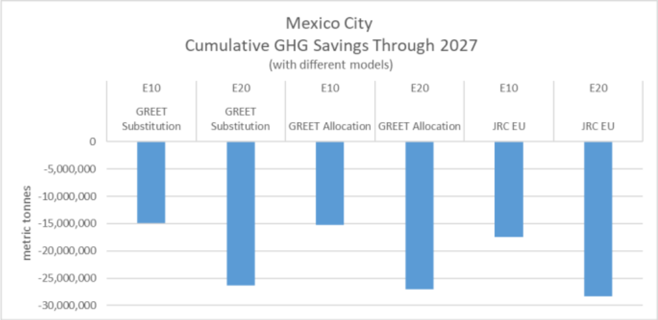
The table below shows the modeling results by city, life cycle model, and ethanol blend. The energy-weighting of each gasoline blending component is used to determine the GHG value of the currently used baseline gasolines which is a blend of either gasoline and MTBE (for Mexico City, New Delhi, Beijing) or gasoline and ETBE (for Tokyo) or gasoline without MTBE/ETBE. (The GHG emissions for gasoline from New Delhi has additionally been reduced by 1.5gCO_2/MJ to reflect the less complex configuration of the oil refineries). These values are then compared to the GHG emissions of the finished E10 and E20 fuels which are derived by proportionally blending the imported US produced ethanol with each country's baseline gasolines. Note that additional likely GHG reductions from streamlined refinery operations in each country were not considered due to modeling complexity. Finally, we derived the cumulative GHG savings for each ethanol blend through 2027 from the total fuel use in each city.

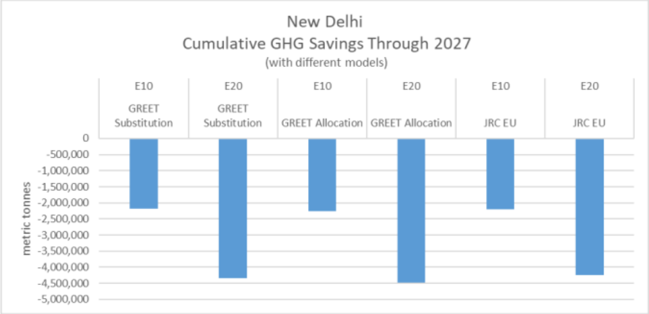
Table 27: Cumulative GHG Emissions and GHG Values of Gasoline and Ethanol Blends

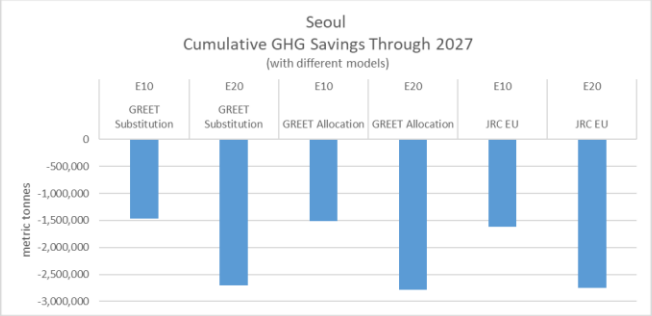
City	Blend	LCA Model	Current Gasoline Blend	Ethanol	Ethanol Blend	GHG Savings: Ethanol Blend to Gasoline	Cumulative GHG Savings
			gCO2/MJ	gCO2/MJ	gCO2/MJ	%	Metric Tonnes
Beijing	E10	GREET Substitution	96.0	49.9	92.1	4.0%	-10,615,326
Beijing	E20	GREET Substitution	96.0	49.9	88.9	7.4%	-19,499,582
Beijing	E10	GREET Allocation	96.0	48.3	92.0	4.1%	-10,915,333
Beijing	E20	GREET Allocation	96.0	48.3	88.7	7.6%	-20,121,184
Beijing	E10	JRC EU	85.3	42.2	81.0	5.0%	-11,731,099
Beijing	E20	JRC EU	85.3	42.2	78.1	8.5%	-19,904,712
Mexico City	E10	GREET Substitution	96.5	43.2	91.7	5.0%	-14,893,452
Mexico City	E20	GREET Substitution	96.5	43.2	88.0	8.8%	-26,366,559
Mexico City	E10	GREET Allocation	96.5	41.5	91.6	5.1%	-15,230,325
Mexico City	E20	GREET Allocation	96.5	41.5	87.8	9.1%	-27,064,546
Mexico City	E10	JRC EU	86.2	34.8	80.5	6.6%	-17,496,494
Mexico City	E20	JRC EU	86.2	34.8	77.0	10.6%	-28,308,137
New Delhi	E10	GREET Substitution	93.9	49.4	90.7	3.4%	-2,181,807
New Delhi	E20	GREET Substitution	93.9	49.4	87.6	6.8%	-4,332,611
New Delhi	E10	GREET Allocation	93.9	47.8	90.6	3.5%	-2,256,084
New Delhi	E20	GREET Allocation	93.9	47.8	87.3	7.0%	-4,486,510
New Delhi	E10	JRC EU	84.2	41.7	81.0	3.8%	-2,193,193
New Delhi	E20	JRC EU	84.2	41.7	78.0	7.4%	-4,242,740
Seoul	E10	GREET Substitution	96.1	49.7	92.2	4.0%	-1,468,176
Seoul	E20	GREET Substitution	96.1	49.7	88.9	7.4%	-2,699,014
Seoul	E10	GREET Allocation	96.1	48.1	92.1	4.2%	-1,509,496
Seoul	E20	GREET Allocation	96.1	48.1	88.7	7.7%	-2,784,626
Seoul	E10	JRC EU	85.3	42.0	81.0	5.0%	-1,622,789
Seoul	E20	JRC EU	85.3	42.0	78.0	8.5%	-2,754,358
Tokyo	E10	GREET Substitution	93.7	49.2	92.2	1.7%	-1,107,776
Tokyo	E20	GREET Substitution	93.7	49.2	88.9	5.2%	-3,412,877
Tokyo	E10	GREET Allocation	93.7	47.5	92.0	1.8%	-1,184,231
Tokyo	E20	GREET Allocation	93.7	47.5	88.6	5.4%	-3,571,289
Tokyo	E10	JRC EU	83.2	41.4	81.3	2.4%	-1,374,099
Tokyo	E20	JRC EU	83.2	41.4	78.2	6.0%	-3,513,337

The total cumulative GHG savings are also graphically represented in the figure below. The GHG savings are remarkably similar regardless of the employed modeling methodology. Cities with high fuel demand and current MTBE use can realize large GHG savings due to the high GHG intensity of the MTBE production pathway.









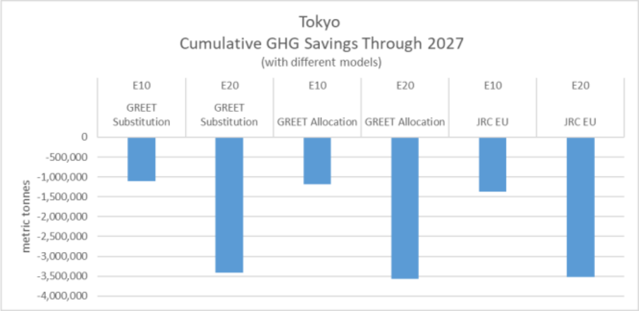
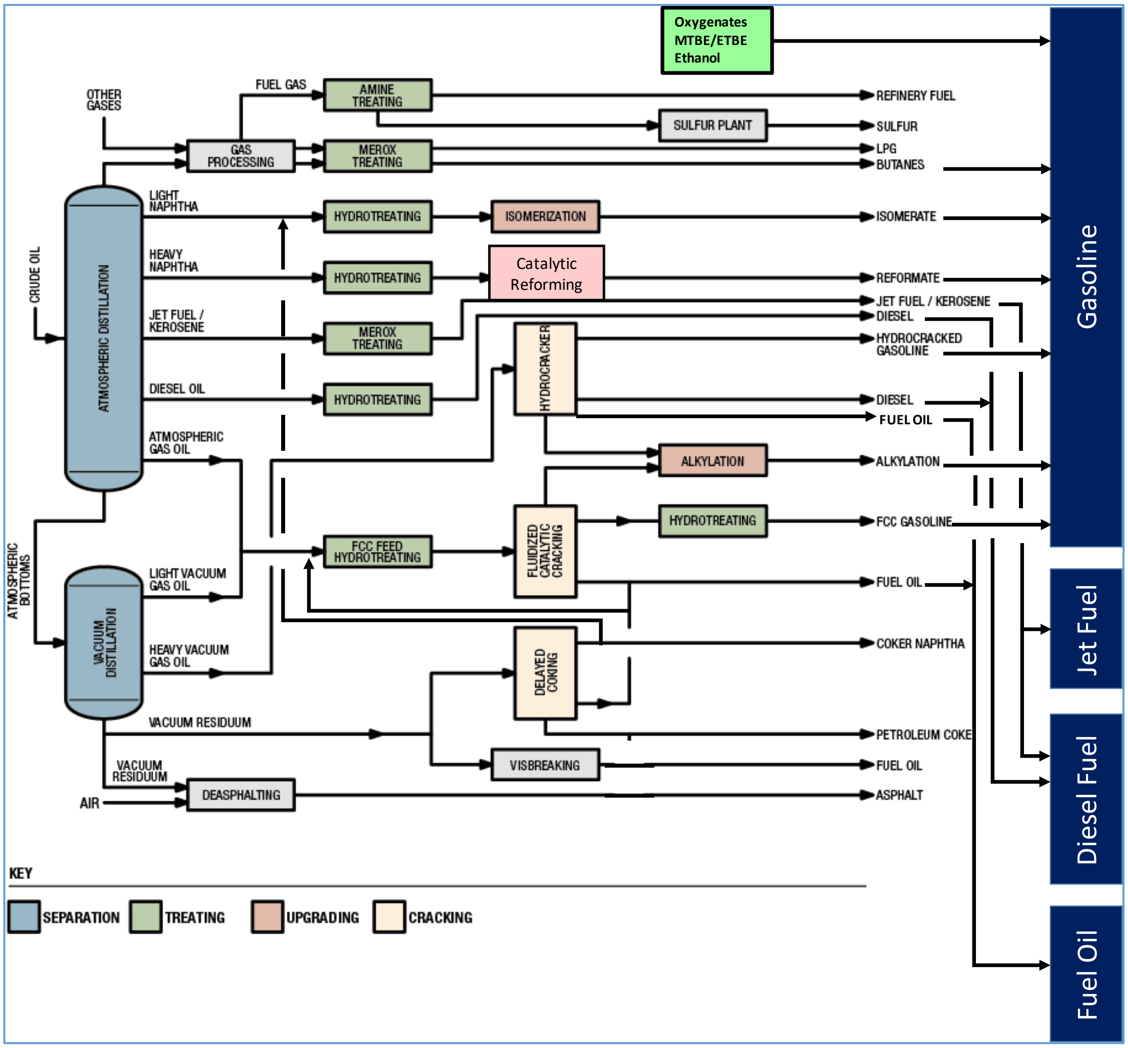


Figure 20: Cumulative GHG Savings by City, Blend, and Model

12 Refining Impact of E10 and E20 Deployment in Each Country

12.1 Petroleum Refining Overview

The processing steps in petroleum refining are designed to convert crude oil primarily into transportation fuels. The first step in refining is fractionation of the petroleum crude oil feed into major components: naphtha, distillate, gas oil, and residual oil (resid or residuum). Subsequent steps convert these streams into lighter components or treat them to improve their quality, for example, by removing sulfur and nitrogen, improving octane or cetane, or making other changes to enable maximum production of the most valuable products. A schematic of a typical refinery is shown in the figure below.



Source: from https://www.mogas.com/en-us/industries/refining with additions

Figure 21: Refinery Schematic

A brief description of the process units follows:

- Atmospheric Distillation Unit also called Crude Distillation Unit or CDU—The crude distillation unit fractionates the crude oil feed into straight run naphtha, kerosene, distillate and heavy atmospheric resid. The CDU is a single column with a one or two-stage preflash and a desalter. Fuel gas, C3s and C4s are sent to the gas plant. Naphtha is sent to the naphtha hydrotreating unit (NHT). Kerosene and atmospheric gas oil go to the DHT (Distillate Hydrotreating Unit). The CDU atmospheric residue bottoms (AR) is sent to the vacuum distillation unit (VDU) for further gas oil recovery.
- Vacuum Distillation Unit or VDU—The vacuum distillation unit (VDU) produces vacuum resid, which is sent to a delayed coking unit, and light and heavy vacuum gas oils (VGOs) are sent to the Gas Oil Hydrotreating Unit (GOHT). The CDU and VDU are heat integrated.
- Delayed Coking Unit—The coking unit converts vacuum resid from the VDU into lighter components, fuel gas, C3 and C4 paraffins and olefins, naphtha, distillate, gas oils and solid petroleum coke product. The delayed coker consists of several coke drums that feed a common fractionator. Fuel gas, C3s and C4s go to the Gas Plant. Naphtha from the coker is routed to the naphtha hydrotreating unit (NHT). The light coker gas oil (LCGO) from the coker is low in cetane number and high in sulfur and requires processing in the distillate hydrotreating unit (DHT). The heavy coker gas oil (HCGO) is further processed in the gas oil hydrotreating unit (GOHT) to achieve the sulfur target. Coke from the delayed coker is routed to sales. The solid coke from this unit can be used as a fuel substitute in power production or cement manufacture or in some cases it is used to make anodes for aluminum production.
- Visbreaking Unit—The Visbreaking unit is an alternative processing route to reduce the amount of vacuum residue that must go to fuel oil if there is no delayed coking unit or other bottoms upgrading unit.
- Gas Oil Hydrotreating Unit or GOHT—The gas oil hydrotreating unit (GOHT) desulfurizes heavy gas oil from the CDU, VDU, and coking units. The level of desulfurization can be set so that the feed to the fluidized catalytic cracking (FCC) unit contains less than 1,000 weight parts per million (ppm) sulfur, which is often sufficient to avoid needing an FCC naphtha hydrotreating unit. The GOHT is a significant user of hydrogen.
- Hydrocracking—The hydrocracking unit is a high pressure unit that cracks gas oil and vacuum gas oil to lighter products in the gasoline and diesel range. Distillate range products are often of high enough quality that they can be blended to products with little or no additional processing. Gasoline range material generally needs further processing – heavy naphtha in a catalytic reforming unit and light naphtha in an isomerization unit. Unconverted product from the hydrocracking unit is an excellent low sulfur feed to the fluidized catalytic cracking unit (FCC) or can be blended to fuel oil.
- Fluidized Catalytic Cracking Unit or FCC—The FCC unit converts heavy gas oils, vacuum gas oils, and heavy hydrotreated gas oils to lighter products. Light cycle oil (LCO) from the FCC unit is sent to the distillate hydrotreating (DHT) unit. FCC naphtha is sent to gasoline blending if it is low enough in sulfur or it can be treated in an FCC naphtha desulfurization unit. Unconverted oil from the FCC unit (called slurry oil) can be blended to fuel oil or recycled to the coking unit to avoid producing fuel oil. The FCC unit consists of a reactor / regenerator, a main fractionator, and a wet gas compressor. Flue gas treating with a third stage separator is generally necessary to meet emission specifications.

- FCC Naphtha Desulfurization Unit—The FCC naphtha desulfurization unit removes sulfur from FCC naphtha to meet low sulfur specifications in most modern gasolines. As a result of olefin saturation during desulfurization, there can be significant octane loss.
- Alkylation—The alkylation unit reacts C3 and C4 olefins with isobutane to produce alkylate for gasoline blending. Purchased isobutane often supplements that produced in the refinery.
- Oligomerization—The oligomerization unit combines mainly C3 olefins but in some cases also C4 olefins into larger, gasoline range molecules. Product octane is lower than alkylate, the product is olefinic, and there is lower yield than from alkylation because this process reacts two olefins together rather than one olefin with one isobutane molecule. Alkylation and oligomerization units convert LPG range material to gasoline.
- Naphtha Hydrotreating Unit or NHT—Naphtha from the CDU, coker, DHT, hydrocracking and GOHT units are hydrotreated in the NHT. The resulting product can be fractionated to send the C6/C7+ components to the catalytic reforming unit and the C5/C6 components to the isomerization unit. The cut-point between light and heavy naphtha can be set to minimize benzene and its precursors in the feed to the catalytic reforming unit. Depending on the feed and degree of desulfurization, the NHT is a low to moderate user of hydrogen.
- Catalytic Reforming Unit or Reformer—The catalytic reforming unit processes heavy naphtha from the naphtha splitter that follows the naphtha hydrotreating unit. The catalytic reforming unit or reformer is the major producer of high octane for gasoline blending. The severity (Research Octane or RON) of the unit is adjusted to meet overall gasoline octane specifications for finished gasoline resulting from blending all gasoline range components. Most of the octane in reformate from the catalytic reforming unit comes from aromatics produced in this process, which results in volume loss due to hydrogen removal in making aromatics. There is also volume loss in catalytic reforming as some naphtha is cracked to gas. The extent of volume loss and gas production depends on the severity that the catalytic reforming unit is operated at: higher severity (RON) results in more octane, hydrogen, and aromatics, but less volume. The catalytic reforming unit is an important source of hydrogen in the refinery.

To meet the benzene limits imposed by gasoline regulations in most countries, the naphtha feed to the catalytic reforming unit can be fractionated in a naphtha splitter to concentrate benzene precursors in light naphtha that can be blended directly to gasoline or processed in a light naphtha isomerization unit. Alternatively to meet benzene specifications, the reformate product from the catalytic reforming unit can be fractionated to produce light and heavy reformate. Light reformate containing most of the benzene is processed together with the light naphtha from the naphtha splitter in the C5/C6 isomerization unit.

When oxygenates are added in gasoline blending, there is less need for octane from the catalytic reforming unit and more hydrotreated naphtha feed to the catalytic reforming unit can be bypassed around this unit and blended directly to gasoline and/or the severity (RON) of the catalytic reforming unit can be reduced. The result is more gasoline production as a result of adding oxygenates and less processing in the catalytic reforming unit. However, as a result of operating at lower severity and processing less feed, there is less hydrogen produced from this unit. Oxygenate addition to gasoline, especially ethanol, can increase gasoline vapor pressure (Reid vapor pressure or RVP) and it may be necessary to remove light components such as butane and sometimes pentanes from the gasoline mix, which results in less gasoline volume. Typical properties of oxygenates are shown in the table below.

Table 28: Oxygenate Properties

	MTBE	ETBE	Ethanol
Blending Octane			
Research Octane (RON)	117	115	*
Motor Octane (MON)	98	98	*
RVP (100 °F), psi	7.8	4.0	*
Oxygen Content, wt%	18.2	15.7	34.8
Specific Gravity	0.746	0.761	0.793

Octane and RVP from ethanol blending depend on the properties of neat gasoline and the amount of ethanol blended.

For most gasoline blends with 10 volume percent (vol%) ethanol

- RVP increases by ~ 1 psi over the RVP of the neat gasoline
- RON increases by ~ 6 RON over the RON of neat gasoline
- MON increases by ~ 3 MON over the MON of the neat gasoline

For most gasoline blends with 20 vol% ethanol

- RVP increases by ~ 1 psi over the RVP of the neat gasoline
- RON increases by ~ 11 RON over the RON of neat gasoline
- MON increases by ~ 5 MON over the MON of the neat gasoline

MTBE and ETBE have RVPs close to typical finished gasoline RVP and thus their addition results in little or no need for butane or pentane removal to meet gasoline RVP specifications. Ethanol has a much bigger impact on RVP and it is generally necessary to remove butane and sometimes even pentanes to enable ethanol blending especially in low RVP gasoline. At 10 vol% in gasoline, ethanol adds around 1 psi to the RVP of the neat gasoline without ethanol.

Ethanol adds more octane than MTBE or ETBE on an equivalent volume basis. In some gasoline blends with ethanol – especially if the gasoline octane specification is low – there is no need for octane from the catalytic reforming unit and there is therefore no hydrogen production from this unit. A refinery producing gasoline with high concentrations of ethanol will need to replace the hydrogen lost from the catalytic reforming, which is usually done by converting natural gas or refinery fuel gas to hydrogen in a steam methane reforming unit (SMR).

- Isomerization Unit or C5/C6 Isom—The isomerization unit is a once-through unit that processes light naphtha and light reformate to increase their research octane from the mid-70s to the low-80s and eliminate benzene. If the feed to the isomerization unit exceeds 5 vol% benzene, a separate benzene saturation reactor is used ahead of the isomerization reactor. The isomerization unit uses a small amount of hydrogen to isomerize the C5/C6 paraffins. Isomerization increases the RVP in the product relative to the feed. Three moles of hydrogen per mole of benzene are used to convert benzene to cyclohexane. A depentanizer can be used ahead of the Isom unit to minimize the RVP impact of isomerization.
- Benzene Saturation—An alternative to eliminating benzene in an isomerization unit is to simply saturate it in a benzene saturation unit. Because there is no isomerization of C5/C6 paraffins that helps offset the octane loss from benzene saturation, it is necessary to operate the catalytic reforming unit at slightly higher severity than when an isomerization unit is used to

eliminate benzene. The net effect is less overall gasoline yield but more hydrogen from the catalytic reforming unit as a result of operating at higher severity.

- Distillate Hydrotreating Unit or DHT—The Distillate Hydrotreating Unit (DHT) reduces sulfur in the distillate range material (kerosene and distillate) from the CDU, coker, GOHT units and sometimes from the hydrocracking unit. In addition, the DHT processes light cycle oil (LCO) from the FCC unit to meet ultra-low sulfur diesel (ULSD) specifications. The DHT unit is a significant user of hydrogen.
- Hydrogen—Hydrogen is produced in the catalytic reforming unit and in the hydrogen plant, by converting natural gas and/or refinery fuel gas to hydrogen via steam methane reforming. Process heat to the hydrogen plant is supplied by fuel gas supplemented by natural gas as needed. The hydrogen plant includes a pressure swing adsorption unit (PSA) to achieve 99%+ purity hydrogen.
- Merox Treating—Merox treating units are relatively low cost units that convert or remove mercaptans from LPG, FCC naphtha, and jet fuel. As refined product sulfur levels are reduced to meet clean fuel specifications, Merox treating is not sufficient and it becomes necessary to hydrotreat FCC naphtha and jet fuel.
- Gas Plants—Gas plants are designed to achieve high recoveries of C3s and C4s. Process units include a Primary Absorber, Stripper, Debutanizer, and Amine Treating.
- Sulfur Plant—Sulfur is recovered in the sulfur plant from H2S that is produced during the refining steps. The sulfur plant consists of a Claus unit, Tail Gas Treating Plant, Amine Regeneration, and Sour Water stripper.

The major products from petroleum refining are transportation fuels – gasoline, jet fuel, and diesel fuel. Fuel oil for stationary use and for ships (bunker fuel) is produced from heavy material that the refinery cannot process or upgrade. Fuel oil is a declining market. New regulations on bunker fuel sulfur go into effect in 2020, which will affect bunker fuel demand. Growing international trade in liquefied natural gas (LNG) and the drop in its price puts further pressure on fuel oil demand.

Petroleum refineries also produce products for the petrochemical industry. These can be propylene, other olefins and diolefins, naphthas, and aromatics. In addition, petroleum refineries produce asphalt for roads and a host of other specialty products.

Transportation fuels from petroleum are increasingly augmented with fuels from other sources. Gasoline is often blended with oxygenates, which can be MTBE, ETBE, or ethanol. Diesel can be blended with biodiesel, a fatty acid methyl ester with methanol (FAME) produced from bio-derived fats and oils. Or diesel can be blended with renewable diesel, a paraffin made from hydrotreating bio-derived fats and oils. Jet fuel can be augmented with renewable jet fuel, which is similar to renewable diesel.

12.2 Refining Industry Profile

The refining industries supplying fuels to the five cities analyzed in this study are very different as are the fuel specifications, fuel demand, and fuel demand growth. A brief description of the major characterizations of the petroleum refining industries and demand for products from petroleum in each country follows.

12.2.1 China

China is a rapidly growing economy with high demand for refined products. The following description of major trends in China is from the latest country report by the U.S. Energy Information Administration (EIA).

Annual growth in oil consumption in China has come down from 11% in 2010, reflecting the effects of the most recent global financial and economic downturn as well as policies in China to reduce excessive investment and capacity overbuilding. Despite slower growth, China still accounted for more than one-third of global oil demand growth in 2014, according to estimates by the EIA.

The EIA forecasts that China's oil consumption will exceed that of the United States by 2034. China's demand growth for oil products has decelerated following a growth spike in 2010. Diesel (gasoil) is a key driver of China's oil products demand and accounted for an estimated 34% of total oil products demand in 2014. Diesel demand declined on an absolute level in 2014 for the first time in two decades, as a result of several factors—slower economic growth, decreased production from the coal and mining sectors that transport products via rail and trucks, greater efficiency in heavy-duty vehicles, and increased use of natural gas fired vehicles in recent years.

Gasoline, the second-largest consumed petroleum fuel in China with an estimated 23% share in 2014, is still experiencing robust demand growth as a result of high light-duty car sales. China's middle class has expanded in the past decade, giving rise to high car sales. Future gasoline consumption will depend on the pace of economic development and income growth, fuel efficiency rates, and government regulations on passenger vehicle use in certain congested urban areas. Liquefied petroleum gas continues to experience some growth from the petrochemical industry, while fuel oil demand has weakened considerably.

China has steadily expanded its oil refining capacity to meet its strong demand growth and to process a wider range of crude oil types. The country now ranks behind only the United States and the European Union in the amount of refining capacity. China's installed crude refining capacity reached nearly 14.2 million barrels per day (BPD) by 2015, about 680,000 BPD higher than in 2013.

Some of the new refineries are designed to accept all grades of crude oil, making Chinese refineries a strong regional competitor. The country intends to meet its domestic demand, which has grown rapidly in the past several years, but also to export petroleum products within the region. Refinery utilization rates have declined to less than 75% in the past year as Chinese companies continued to build refining capacity against a backdrop of slower oil demand growth in China and around the world.

The National Development and Reform Commission (NDRC) claims that incremental refining capacity is expected to be 3.4 million BPD between 2016 and 2020. However, industry analysts anticipate China would add only 1.5 million BPD of net capacity between 2015 and 2020, as a result of several project delays and overcapacity during the past two years.

Recent heavy pollution in certain areas of China prompted the NDRC to adopt stricter petroleum product specifications that are intended to lower sulfur emissions from gasoline and diesel use. The agency requires refineries to implement the equivalent of Euro IV standards for transportation fuels nationwide in 2015 and Euro V standards by January 2017, a year ahead of the prior schedule. Shanghai and Beijing are already supplying only fuels that meet Euro V standards. Sinopec and CNPC are investing in refinery upgrades to meet these emissions standards, but the small independent refineries are facing economic challenges of additional cost.

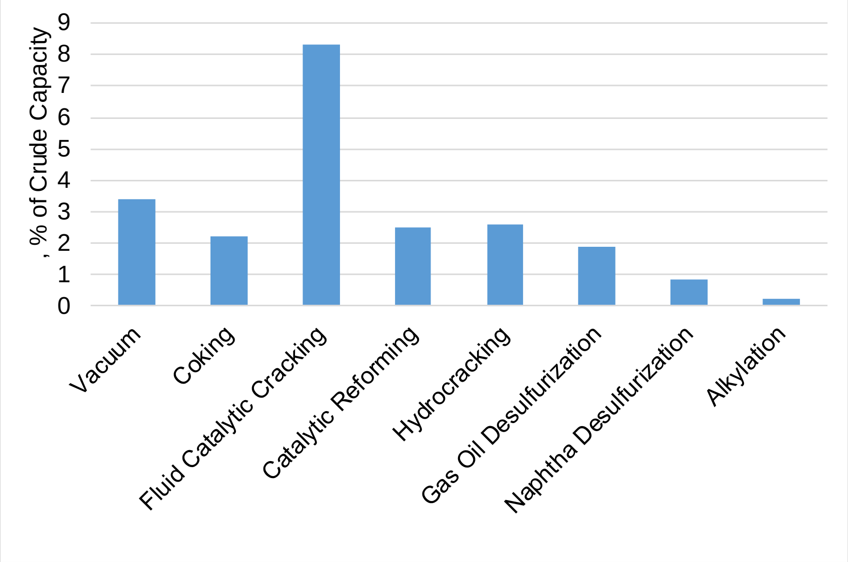
The two primary oil companies in China: are China National Petroleum Corporation (CNPC) and Sinopec. In addition, two other companies also operate in China, West Pacific Petrochemical Corp and Yanan. Crude Oil Distillation capacity in 2014 was broken down as follows:

Table 29: Crude Oil Distillation Capacity -China

	Crude Distillation Capacity, BPD
China National Petroleum Corp	2,875,000
Sinopec	3,971,000
West Pacific Petrochemical Corp.	160,000
Yanan Refinery	60,000

Source: Pennwell Worldwide Refining Survey, 2014

The breakdown of Chinese refining capacity by major processing units as percent of crude oil distillation capacity is shown below.



Source: Pennwell Worldwide Refining Survey, 2014

Figure 22: Refining Capacity - China

12.2.2 Mexico

Mexico is a developing country with slow growth in demand for refined products. Despite being one of the leading oil producers in the world, as a result of under-investment in its oil sector by its state owned oil monopoly, PEMEX, Mexico is highly dependent on imports of refined products to meet domestic demand. The following description of major trends in Mexico is from the latest country report by the U.S. Energy Information Administration (EIA).

Mexico is one of the largest producers of petroleum and other liquids in the world. Mexico is also the fourth-largest producer in the Americas after the United States, Canada, and Brazil, and an important partner in U.S. energy trade. Despite its status as a large crude oil exporter, Mexico is a net importer of refined petroleum products. According to PEMEX, Mexico imported 740,000 BPD of refined petroleum products in 2015, of which 58% was gasoline, and most of the remainder was diesel and liquefied petroleum gases (LPG). Mexico was the destination for 50% of U.S. exports of motor gasoline in 2015.

In 2015, Mexico exported 195,000 BPD of refined petroleum products. The United States imported 70,000 BPD of that export total, most of which was residual fuel oil, naphtha, and pentanes plus. As with crude oil, U.S. imports of refined petroleum products from Mexico have declined in recent years, from a high of 132,000 BPD in 2010.

PEMEX operates an extensive petroleum pipeline network in Mexico that connects major production centers with domestic refineries and export terminals. According to PEMEX, this network consists of pipelines spanning more than 3,000 miles, with the largest concentration occurring in southern Mexico.

Mexico’s total oil consumption remained relatively steady over the past decade, averaging about 1.7 million BPD in 2015. According to Mexican government data, gasoline accounted for roughly 46% of the country’s petroleum product sales in 2015, and diesel accounted for another 23%.

Mexico’s six refineries, all operated by PEMEX, had a total refining capacity of 1.54 million BPD as of the end of 2015. According to PEMEX, refinery output was 1.27 million BPD in 2015, a 9% decline from 2014. PEMEX also controls 50% of the 334,000 BPD Deer Park refinery in Texas.

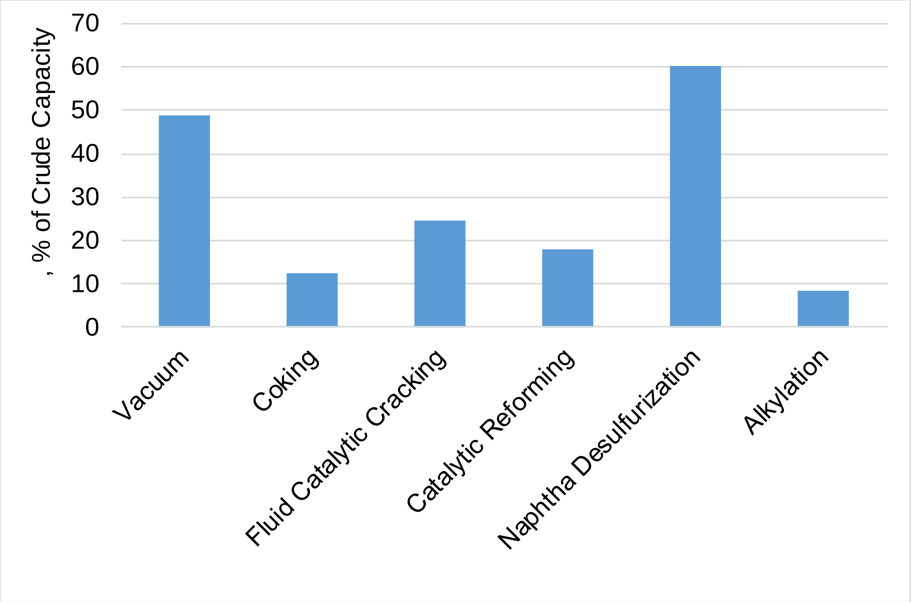
Mexico hopes to reduce its imports of refined products by improving domestic refining capacity and the output quality. In February 2012, PEMEX awarded a contract for the design of a new refinery at Tula, but in December 2014 the company opted for a $4.6 billion expansion of the existing facility. Gasoline and diesel production will increase from 140,000 BPD to 300,000 BPD at Tula when it is completed in 2018. Despite this and other expansions, analysts contend that Mexico does not have a natural competitive advantage in refining, given the country’s close proximity to a sophisticated U.S. refining center. Some analysts feel that it would be more productive to apply PEMEX’s limited capital to the upstream sector.
Source: https://www.eia.gov/beta/international/analysis.cfm?iso=MEX
The breakdown of crude oil distillation capacity in Mexico is shown in below.

Table 30: Crude Oil Distillation Capacity – Mexico

	Crude Distillation Capacity, BPD
Pemex	1,540,000

Source: Pennwell Worldwide Refining Survey, 2014

The breakdown of Mexican refining capacity by major processing units as percent of crude oil distillation capacity is shown below.



Source: Pennwell Worldwide Refining Survey, 2014

Figure 23: Refining Capacity - Mexico

12.2.3 India

India is a rapidly growing economy with high demand for refined products. The following description of major trends in India is from the latest country report by the U.S. Energy Information Administration (EIA).

India was the fourth-largest consumer of crude oil and petroleum products after the United States, China, and Japan in 2015, and it was also the fourth-largest net importer of crude oil and petroleum products. The gap between India's oil demand and supply is widening, as demand in 2015 reached nearly 4.1 million BPD, compared to around 1 million BPD of total domestic liquids production. The EIA expects demand to accelerate in the 2016 through 2017 timeframe as India's transportation and industrial sectors continue to expand under economic development.

The refining industry is an important part of India's economy. The state-owned company, Oil India Limited (IOCL), holds most of the refining activity in India. Private Indian companies like Reliance Industries (RIL) and Essar Oil have become major refiners. The private sector owns about 37% of total capacity. In early 2016, India had 4.6 million BPD of nameplate refining capacity, making it the second-largest refiner in Asia after China.

The two largest refineries by crude capacity, located in the Jamnagar complex in Gujarat, are world-class export facilities and are owned by Reliance Industries. The Jamnagar refineries account for 26% of India's current capacity. These refineries are on the country's western coast close to crude oil-producing regions in the Middle East, which allows them to take advantage of lower transportation costs.

India projects an increase of the country's refining capacity to 6.3 million BPD by 2017 based on its current five-year plan to meet rising domestic demand and supply export markets, although several refinery projects have faced delays in the past few years as a result of financial issues, bad weather, and regulatory hurdles. Also, there is now greater competition in Asia from countries such as China that have built large refineries able to process more complex crude oil types.

After several years of delays, India's new Paradip refinery in Odisha began commercial operations in 2016 and added about 300,000 BPD of capacity. This refinery is one of India's most complex facilities with the ability to process more sulfurous sour crude oil grades and maximize production of high-valued oil products such as diesel and gasoline.

India's government started encouraging energy companies to invest in refineries at the end of the 1990s, and the investment helped the country become a net exporter of petroleum products in 2001. In particular, the government eliminated customs duties on crude imports, lowering the cost of fuel supply for refiners. These reforms made domestic production of petroleum products more economic for Indian companies. In its 11th Five Year Plan (2007-12), India's government set the goal of making India a global exporting hub of refined products. Between 2005 and 2013, India's oil product exports, mostly from gasoil and gasoline, almost tripled to more than 1.3 million BPD before falling back to less than 1.2 million BPD in 2015 as domestic demand for products escalated at a faster pace. Some export-oriented refineries began reorienting oil production for domestic use in 2009 to help ease shortages of motor gasoline, gasoil, kerosene, and liquefied petroleum gas (LPG).

Diesel remains the most-consumed oil product, accounting for 41% of petroleum product consumption in 2015 and is used primarily for commercial transportation and, to a lesser degree, in the industrial, electric power, and agricultural sectors. Following the government's lifting of diesel subsidies during 2013 and 2014 and attendant higher retail prices that ensued, diesel demand growth flattened during this period before rising again in 2015. Gasoline use has increased at a fast pace over the past decade, and in the past few years, this fuel has replaced some diesel in the transportation sector.

Indian companies have plans to upgrade several existing refineries to produce higher-quality auto fuels to comply with more stringent specifications for vehicle fuel standards. India plans to adopt the equivalent of Euro IV fuel efficiency standards on a nationwide basis by April 2017 and both Euro V and Euro VI standards on transportation fuels by 2020. Indian companies have proposed several expansions to existing facilities and new refineries by 2020, although the timeline of these projects depends on the success of project investments and fuel sales in both domestic and export markets.

Source: https://www.eia.gov/beta/international/analysis.cfm?iso=IND

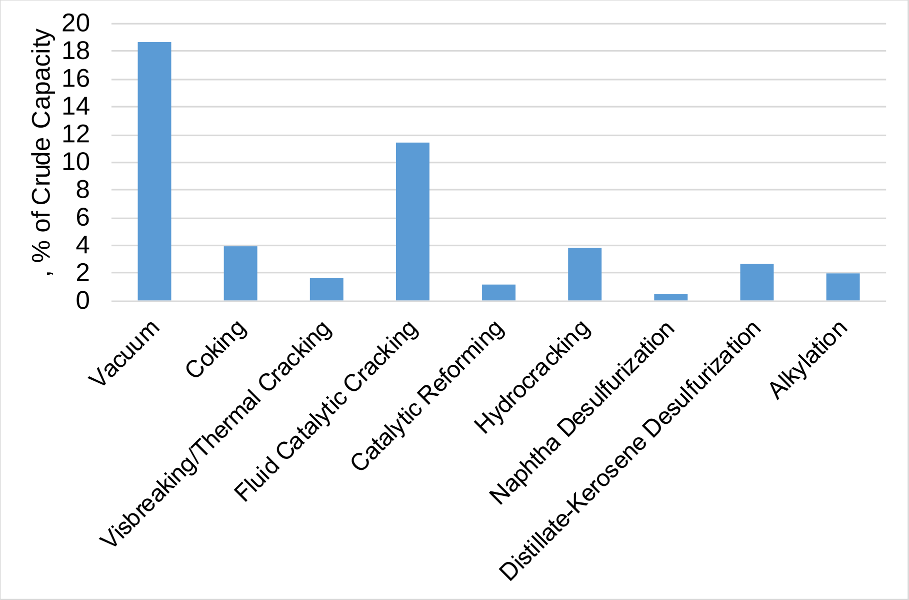
The breakdown of crude oil refining capacity in India by company is shown below.

Table 31: Crude Oil Distillation Capacity – India

	Crude Distillation Capacity, BPD
Reliance	1,240,000
Indian Oil Corp	1,146,796
Bharat Petroleum Corp	465,344
Essar Refinery	405,000
Hindustan Petroleum Corp	298,000
Chennai Petroleum Corp. Ltd.	227,261
Mangalore Refinery & Petrochemicals Ltd.	194,000
HCPL-Mittal Energy Ltd.	180,000
Bharat Oman Refineries Ltd.	120,000
Numaligarh Refinery Ltd.	64,932
Oil & Natural Gas Corp. Ltd.	1,428

Source: Pennwell Worldwide Refining Survey, 2014

The breakdown of Indian refining capacity by major processing units as percent of crude oil distillation capacity is shown below.



Source: Pennwell Worldwide Refining Survey, 2014

Figure 24: Refining Capacity - India

12.2.4 South Korea

South Korea is a developed country and has a flat to declining demand for refined products. The following description of major trends in South Korea is from the latest country report by the U.S. Energy Information Administration (EIA).

Despite its lack of domestic energy resources, South Korea is home to some of the largest and most advanced oil refineries in the world. Although petroleum and other liquids, including biofuels, accounted for the largest portion (41%) of South Korea's primary energy consumption in 2015, liquid fuel's share has been declining since the mid-1990s, when it reached a peak of 66%.This trend is attributed to the steady increase in natural gas, coal, and nuclear energy consumption, which has reduced oil use in the power sector and the industrial sector. Higher vehicle efficiencies have also reduced oil consumption.

According to the Oil & Gas Journal (OGJ), 3 of the 10 largest crude oil refineries in the world are located in South Korea, making it one of Asia's largest petroleum product exporters. According to Facts Global Energy (FGE), South Korea exported about 1.3 million BPD of refined oil products in 2015, mostly in the form of middle distillates such as gasoil, gasoline, and jet fuel. Oil product imports, about 0.9 million BPD in 2015, were primarily naphtha and LPG. Because of increased demand in Asia during the past decade, South Korea's exports of refined products have grown rapidly. The future growth rate of oil product exports will depend on demand from regional trading partners, which has been weak over the past few years, and on rising competition from new Asian and Middle Eastern refineries.

Korea's downstream sector includes several large international oil companies including SK Energy, the nation's largest international oil company (IOC). SK Energy is the largest marketer of petroleum products, followed by GS Caltex, S-Oil, and Hyundai Oilbank. These companies have historically focused on refining, but some have put increasing emphasis on crude oil extraction projects in other countries. SK Energy also owns the largest stake in the Daehan Oil Pipeline Corporation (DOPCO), which exclusively owns and manages South Korea's oil pipelines, although most of the country's oil is distributed by tankers or trucks.

According to OGJ, South Korea had about 3 million BPD of crude oil distillation refining capacity at the end of 2016 and ranked sixth largest for refining capacity in the world. The country's three largest refineries are owned by SK Energy, GS Caltex, and S-Oil Corporation (partially owned by Saudi Aramco).

Korean refineries are increasingly producing light, clean oil products as a result of refinery upgrades in recent years. The high degree of sophistication of South Korean refineries results in high capacity utilization. As a result, South Korea is expected to remain a leading refiner in Asia, with significant exports to other Asian countries. Recently, South Korean refiners have faced the headwinds of slower demand in export markets in recent years, although lower oil prices boosted refining margins in 2015.

In response to South Korea's diversification of its energy portfolio over the past few decades, oil companies not only upgraded refining facilities and increased upstream investment, but they also began investing in oil storage and alternative energy projects.

Source: https://www.eia.gov/beta/international/analysis.cfm?iso=KOR

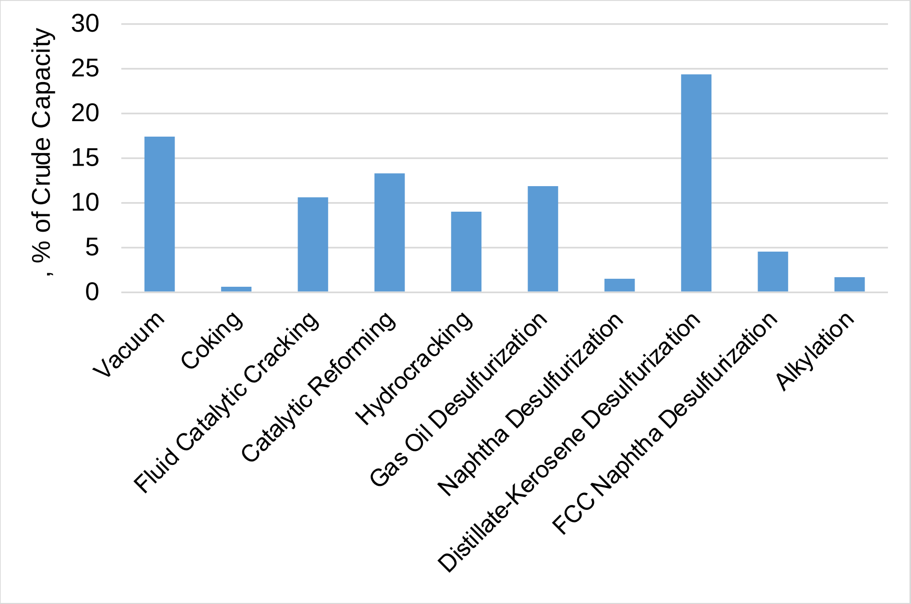
The breakdown of crude oil distillation capacity in South Korea is shown in below.

Table 32: Crude Oil Distillation Capacity – South Korea

	Crude Distillation Capacity, BPD
SK Innovation	1,115,000
GS Caltex Corp.	775,000
S-Oil Corp.	669,000
Hyundai Oilbank Corp.	390,000
Hyundai Lube Oil	9,500

Source: Pennwell Worldwide Refining Survey, 2014

The breakdown of South Korean refining capacity by major processing units as percent of crude oil distillation capacity is shown in Figure x-5.



Source: Pennwell Worldwide Refining Survey, 2014
Figure 25: Refining Capacity – South Korea

12.2.5 Japan

Japan is a developed country and has a flat to declining demand for refined products. The following description of major trends in Japan is from the latest country report by the U.S. Energy Information Administration (EIA).

Japan consumed an estimated 4 million BPD in 2016, making it the fourth-largest petroleum consumer in the world, behind the United States, China, and India. However, oil demand in Japan has declined by 23% overall since 2006. This decline results from structural factors, such as fuel substitution, a declining and an aging population, and energy efficiency measures.

Japan consumes most of its oil in the transportation and industrial/chemical sectors (about 43% and 30% of petroleum products, respectively, in 2013). In addition to being highly dependent on petroleum imports it is also highly dependent on naphtha and liquefied petroleum gases (LPG) imports.

Private Japanese firms dominate the country's large and competitive downstream sector, as foreign companies have historically faced regulatory restrictions. But over the past several years, these regulations have been eased, which has led to increased competition in the petroleum-refining sector. Chevron, BP, Shell, and BHP Billiton are among the foreign energy companies involved in providing products and services to the Japanese market as well as joint venture (JV) partnerships in many of Japan's overseas projects.

According to the Petroleum Association of Japan (PAJ), Japan had 3.8 million BPD of crude oil refining capacity at 22 facilities as of October 2016. Japan has the fourth-largest refining capacity globally, behind the United States, China, and India. JX Holdings is the largest of eight oil refinery companies in Japan, and other key operators include Idemitsu Kosan, Cosmo Oil, TonenGeneral Sekiyu, and Showa Shell Group. In recent years, the refining sector in Japan has encountered excess capacity because domestic petroleum product consumption has declined. This decline is a result of the contraction of industrial output, the mandatory blending of ethanol (often as ETBE) into transportation fuels, more fuel-efficient vehicles, and shifting demographics leading to less driving each year. In addition to declining domestic demand for oil products, Japanese refiners now must compete with new, sophisticated refineries in emerging Asian markets.

The Japanese government seeks to promote operational efficiency in the refining sector, including increasing refinery competitiveness, which may lead to further refinery closures in the future. As a result, Japan has scaled back refining capacity from about 4.7 million BPD less than a decade ago. In 2010, METI announced an ordinance that would raise refiners' mandatory cracking-to-crude distillation capacity ratio from 10% to 13% or higher by March 2014. To adhere to METI's directive, some refiners reduced capacity by nearly 20% between April 2010 and April 2014 by closing plants entirely or by consolidating facilities. METI initiated a second phase of refinery restructuring, which involved improving the overall processing capacity to 50% from a current overall processing capacity of 45% and affected a broader range of processing units. The government calls for this phase to be implemented by March 2017, with a goal that an estimated 400,000 BPD of capacity will be curtailed through further reductions in refining operations and facility closures.

There has been discussion that METI could issue a third phase to further consolidate the number of refiners and the total capacity, although no details about this phase are available. These capacity reductions come at a time when the country's oil demand continues to decline as a result of an aging population, energy conservation measures, expectations of nuclear facilities returning to serve the power sector, and financial burdens of companies having to upgrade and maintain Japan's old refining plants.

In 2015, two large mergers of refining corporations were proposed, one between JX Holdings and TonenGeneral and the other between Idemitsu Kosan and Showa Shell Group. JX Holdings and TonenGeneral plan to reduce their combined refinery capacity in the Chiba area, to share infrastructure, and to gain a majority share of the country's gasoline retail market. Final approval and completion of this merger is expected by April 2017. The Idemitsu/Showa Shell merger has been held up by recent resistance from the Idemitsu founding family, who claims that the two companies have different corporate cultures. This potential merger block could delay further refining capacity reduction in Japan. Source: https://www.eia.gov/beta/international/analysis.cfm?iso=JPN

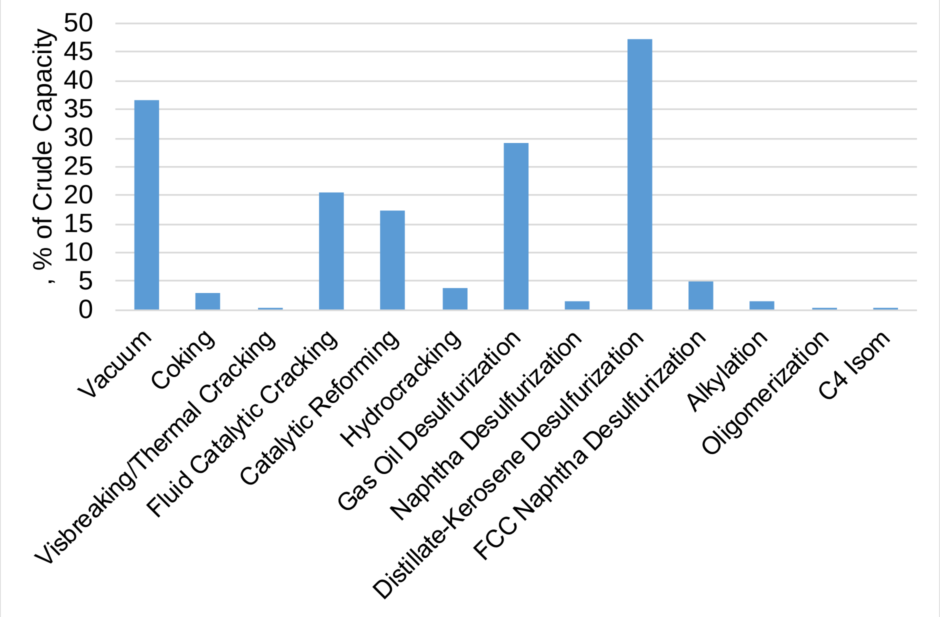
The breakdown of crude oil distillation capacity in Japan by company is shown in below.

Table 33: Crude Oil Distillation Capacity – Japan

	Crude Distillation Capacity, BPD
JX Nippon Oil & Energy	1,423,200
Idemitsu Kosan	608,000
Tonen/General Sekiyu Seisei KK	595,500
Cosmo Oil Co. Ltd.	451,250
Japan Energy Corp.	194,940
Fuji Oil Co. Ltd.	192,000
Kashima Oil Co. Ltd.	180,500
Toa Oil Co	175,000
Kyokuto Petroleum Industries Ltd.	171,500
Taiyo Oil Co. Ltd.	120,000
Seibu Oil Co. Ltd.	111,000
Nansei Sekiyu KK	100,000
Okinawa Sekiyu Seisei	100,000

Source: Pennwell Worldwide Refining Survey, 2014

The breakdown of Japanese refining capacity by major processing units as percent of crude oil distillation capacity is shown below.



Source: Pennwell Worldwide Refining Survey, 2014

Figure 26: Refining Capacity – Japan

13 Impact on Refining Profits

The table below shows the net revenue impact from changes in hydrogen and gasoline production relative to the Base Case for each city. The assumed prices were as follows:

- Gasoline price: average spot price per gallon for NY Harbor for conventional gasoline from July 2016 to July 2017 - from the EIA.
- Natural gas: city gate price for natural gas from July 2016 to June 2017 - from the EIA.

The cost of hydrogen was calculated from the cost of natural gas using yields from a steam methane reforming unit hydrogen plant model operating on natural gas and steam. An estimate of additional operating costs for the hydrogen plant is included. As shown in the tables the incremental hydrogen and incremental gasoline were determined for each case vs. the Base Case for each city. The results are shown on the basis of barrels of gasoline in the Base Case for each city. As can be seen in the individual tables and the summary graph below all ethanol blended fuels return equal or increased revenue for refiners.

Table 34: Beijing Refining Cost

		Beijing		
		MTBE	E10	E20
CHANGE FROM BASE		Base		
Change in Production				
Hydrogen Production	MM SCFD	10.41	5.43	2.17
Gasoline Volume	BPD	10,176	10,590	12,132
Delta Hydrogen	MM SCFD	0.00	-4.98	-8.24
Delta from Base Gasoline	BPD	0	414	1,955
Prices - Avg July 2016 to June 2017				
Natural Gas Price - City Gate	$/1000 SCF	4.25	4.25	4.25
Hydrogen Price	$/1000 SCF	2.68	2.68	2.68
Gasoline Price	$/gal	1.50	1.50	1.50
Incremental Revenue				
Revenue from Hydrogen	$/Day	0	-13,351	-22,115
Revenue from Gasoline	$/Day	0	26,133	123,478
Net Revenue	$/Day	0	12,781	101,362
Net Revenue per barrel Base Gasoline	$/Bbl Base Gasoline	$0	$1	$10

Table 35: Mexico City Refining Cost

		Mexico City		
		MTBE	E10	E20
CHANGE FROM BASE		Base		
Change in Production				
Hydrogen Production	MM SCFD	51.81	43.01	28.38
Gasoline Volume	BPD	46,464	46,587	52,176
Delta Hydrogen	MM SCFD	0.00	-8.80	-23.43
Delta from Base Gasoline	BPD	0	123	5,712
Prices - Avg July 2016 to June 2017				
Natural Gas Price - City Gate	$/1000 SCF	4.25	4.25	4.25
Hydrogen Price	$/1000 SCF	2.68	2.68	2.68
Gasoline Price	$/gal	1.50	1.50	1.50
Incremental Revenue				
Revenue from Hydrogen	$/Day	0	-23,571	-62,740
Revenue from Gasoline	$/Day	0	7,761	360,725
Net Revenue	$/Day	0	-15,810	297,985
Net Revenue per barrel Base Gasoline	$/Bbl Base Gasoline	$0	$0	$6

Table 36: New Delhi Refining Cost

		New Delhi		
		MTBE	E10	E20
CHANGE FROM BASE		Base		
Change in Production				
Hydrogen Production	MM SCFD	5.37	0.00	0.00
Gasoline Volume	BPD	11,717	14,171	16,888
Delta Hydrogen	MM SCFD	0.00	-5.37	-5.37
Delta from Base Gasoline	BPD	0	2,454	5,171
Prices - Avg July 2016 to June 2017				
Natural Gas Price - City Gate	$/1000 SCF	4.25	4.25	4.25
Hydrogen Price	$/1000 SCF	2.68	2.68	2.68
Gasoline Price	$/gal	1.50	1.50	1.50
Incremental Revenue				
Revenue from Hydrogen	$/Day	0	-14,395	-14,395
Revenue from Gasoline	$/Day	0	154,952	326,541
Net Revenue	$/Day	0	140,556	312,146
Net Revenue per barrel Base Gasoline	$/Bbl Base Gasoline	$0	$12	$27

Table 37: Seoul Refining Cost

		Seoul		
		No Oxygenates	E10	E20
CHANGE FROM BASE		Base		
Change in Production				
Hydrogen Production	MM SCFD	59.30	39.59	23.28
Gasoline Volume	BPD	23,189	26,269	30,589
Delta Hydrogen	MM SCFD	0.00	-19.71	-36.02
Delta from Base Gasoline	BPD	0	3,081	7,400
Prices - Avg July 2016 to June 2017				
Natural Gas Price - City Gate	$/1000 SCF	4.25	4.25	4.25
Hydrogen Price	$/1000 SCF	2.68	2.68	2.68
Gasoline Price	$/gal	1.50	1.50	1.50
Incremental Revenue				
Revenue from Hydrogen	$/Day	0	-52,872	-96,636
Revenue from Gasoline	$/Day	0	194,548	467,358
Net Revenue	$/Day	0	141,676	370,722
Net Revenue per barrel Base Gasoline	$/Bbl Base Gasoline	$0	$6	$16

Table 38: Tokyo Refining Cost

		Tokyo		
		ETBE	E10	E20
CHANGE FROM BASE		Base		
Change in Production				
Hydrogen Production	MM SCFD	51.67	36.69	27.48
Gasoline Volume	BPD	35,083	36,592	41,773
Delta Hydrogen	MM SCFD	0.00	-14.98	-24.19
Delta from Base Gasoline	BPD	0	1,510	6,691
Prices - Avg July 2016 to June 2017				
Natural Gas Price - City Gate	$/1000 SCF	4.25	4.25	4.25
Hydrogen Price	$/1000 SCF	2.68	2.68	2.68
Gasoline Price	$/gal	1.50	1.50	1.50
Incremental Revenue				
Revenue from Hydrogen	$/Day	0	-40,180	-64,892
Revenue from Gasoline	$/Day	0	95,360	422,546
Net Revenue	$/Day	0	55,180	357,654
Net Revenue per barrel Base Gasoline	$/Bbl Base Gasoline	$0	$2	$10

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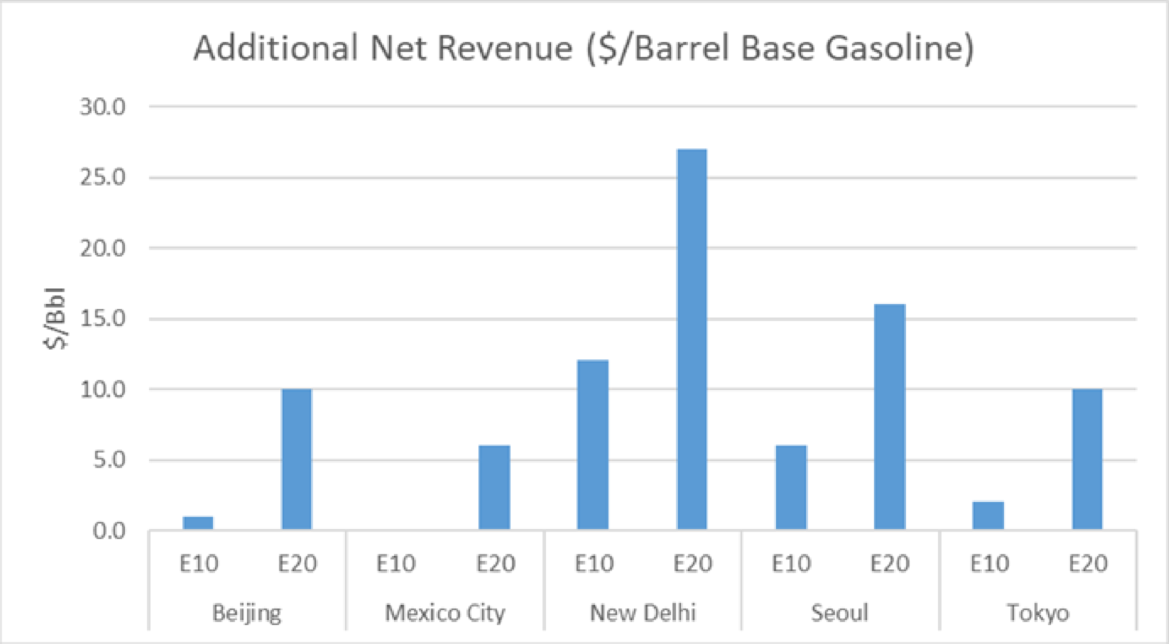


Figure 27: New Revenue Adjustments to Refiners from Adopting Ethanol Blends

14 Health Impacts from Ethanol in Gasoline

This chapter was written in collaboration with Dr. Zigang Dong (Executive Director) and Dr. K. S. Reddy, The Hormel Institute, University of Minnesota. Additional contributions were provided by Dr. Rachel Jones, Associate Professor of Environmental and Occupational Health Sciences, UIC School of Public Health.

This section of the report builds on the results of previous chapters and it completes the integrated approach to assess the pathway of air toxins and other polluting compounds from fuel blending to health impacts.

14.1 Modeling Approach to Assess the Health Impact from Blending Ethanol

The figure below shows the five step process employed in the present study to assess the health impact of ethanol blends across the studied cities. In previous chapters we performed an analysis of the refining impact of adding ethanol and determined the emissions mass reductions in vehicles. Now we convert the mass reductions to concentrations in the atmosphere which then allows us to apply health risk factors and subsequently quantify the impact on cancer cases, health cost, and years of life lost. In the following each step will be detailed.

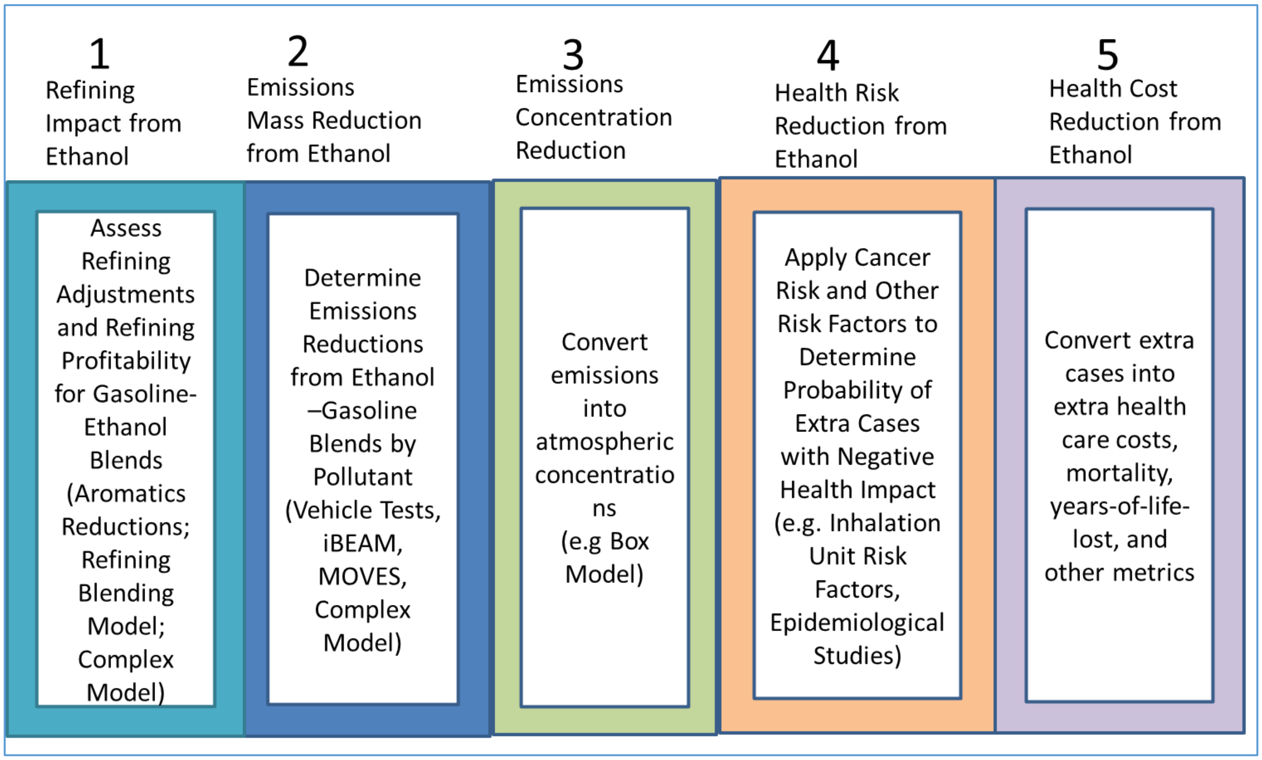


Figure 28: Health Impact Modeling Sequence

Refining Impact from Ethanol

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

The catalytic reforming unit within a refinery is the major producer of high octane for gasoline blending. The severity (Research Octane or RON) of the unit is adjusted to meet overall gasoline octane specifications for finished gasoline resulting from blending all gasoline range components. Most of the octane in reformate from the catalytic reforming unit comes from aromatics produced in this process.

With ethanol blended into gasoline the reforming unit severity is adjusted to lower research octane numbers (RON), which generally results in lower benzene and aromatics content (see Figure below). The recent Fuels Trends Report by the US Environmental Protection Agency discloses the connection between ethanol and aromatics in gasoline and states: “Ethanol’s high octane value has also allowed refiners to significantly reduce the aromatic content of the gasoline, a trend borne out in the data" [45].

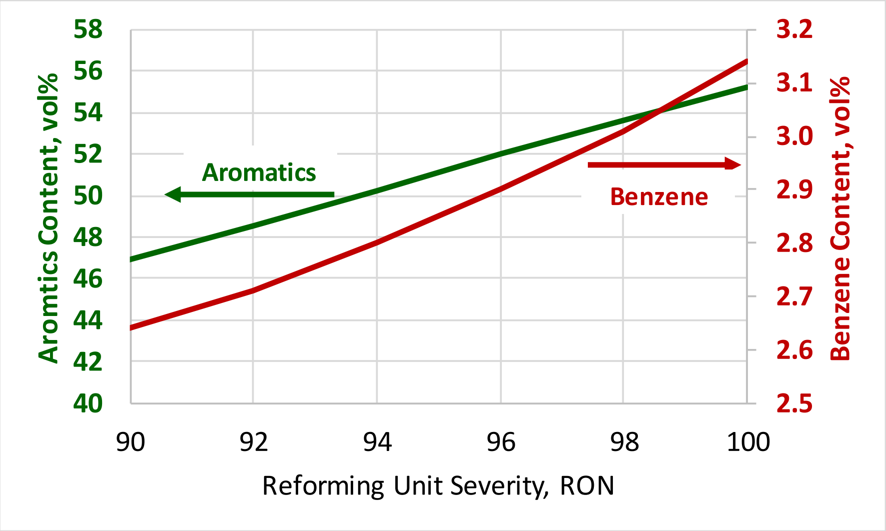


Figure 29: Aromatics Production at Refinery to Meet Octane Requirements

The blending behavior from refiners whereby aromatics are reduced in anticipation of the addition of ethanol was also documented in the present study. The panel of figures below shows the results from a blending model that changes the gasoline recipe based on the addition of ethanol. As can be seen across all cities the aromatics and benzene content drops with the addition of ethanol. Benzene levels may also be separately regulated.

Blending results for Seoul and Beijing show a reduction in benzene and aromatics as ethanol replaces MTBE. Adding ethanol at 10 vol% reduces the need for octane from the catalytic reforming unit and adds volume for dilution. Going to 20 vol% ethanol further reduces benzene and aromatics in the final gasoline blends. Results for Delhi and Tokyo show similar results as for Seoul and Beijing. For Mexico City E20 follows the blending model pattern observed for all cities. However, for Mexico City E10 the blending model would predict about the same addition of aromatics than for the baseline gasoline but the adjustments in the distillation curve from ethanol still results in a reduction of predicted tailpipe emissions.

Figure 30: Projected Blending Behavior of Refiners

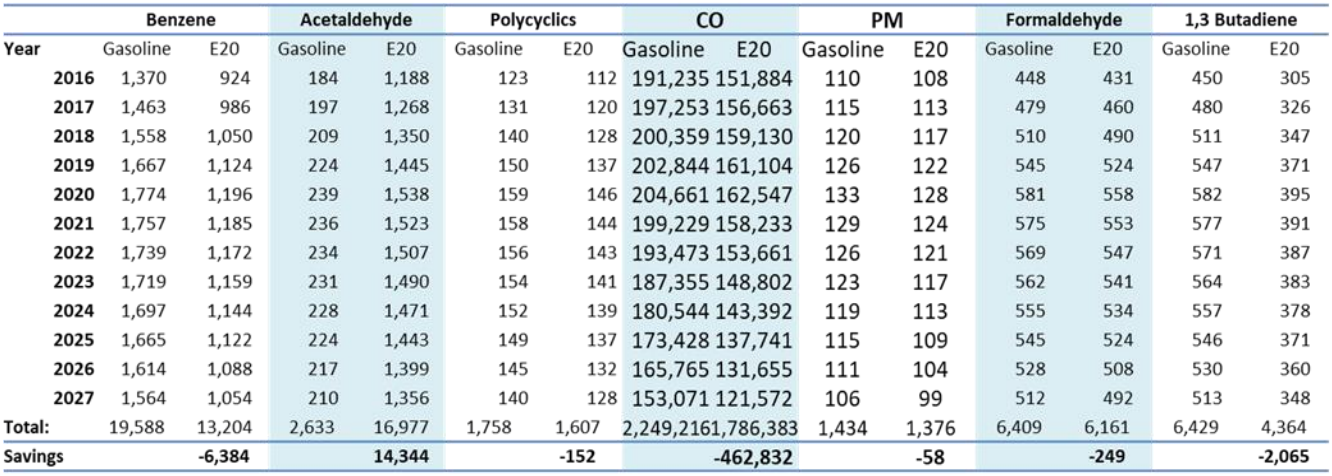
The toxic compounds from the fuel as well as additional compounds formed during the combustion process are either emitted through exhaust, crankcase and evaporative processes. Some of the toxic pollutants affected by ethanol blends are aromatics (e.g. benzene, polycyclic aromatic hydrocarbons also known as PAHs), alkanes (such as butadiene) and aldehydes (e.g. formaldehyde, acetaldehyde).

Emissions Mass Reductions from Ethanol

Besides the fuel formulations the emitted quantities depend on vehicle technology, driving patterns, climate, and geography. In emissions inventory models such as the US EPA's MOtor Vehicle Emission Simulator (MOVES) model the emissions of many of the toxic compounds are estimated as fractions of the emissions of volatile organic compounds (including benzene, butadiene, acetaldehyde, formaldehyde) or for toxic species in the particulate phase (including many PAHs such as Benzopyrene) as fractions of total organic carbon < 2.5 µm [46]. The equations for several toxics are in turn a carry-over from the EPA Complex Model which is used to determine whether gasoline complies with reformulated gasoline (RFG) and anti-dumping emissions performance standards. The Complex Model's original emissions equations derives benzene emissions as a function of a fuel batch's benzene, non-benzene aromatics, and sulfur content, as well as distillation fractions at E200 and E300 [47].

In previous chapters we quantified the emissions reductions (in tonnes) that can be achieved from blending E10 and E20. The mass of emissions reductions depends on the vehicle fleet in each city, fuel consumption, vehicle emissions standards and fuel parameters. For example, the table below lists the expected emissions from gasoline vehicles for the city of Beijing as well as the emissions and emissions savings from a 20% ethanol blend for selected pollutants. As can be seen over the next ten years blending E20 would save a cumulative 6,400 tonnes of benzene emissions into the Beijing air shed.

Table 39: Example of Emissions Reductions from E20 - Beijing



	Benzene		Acetaldehyde		Polycyclics		CO		PM		Formaldehyde		1,3 Butadiene	
Year	Gasoline	E20	Gasoline	E20	Gasoline	E20	Gasoline	E20	Gasoline	E20	Gasoline	E20	Gasoline	E20
2016	1,370	924	184	1,188	123	112	191,235	151,884	110	108	448	431	450	305
2017	1,463	986	197	1,268	131	120	197,253	156,663	115	113	479	460	480	326
2018	1,558	1,050	209	1,350	140	128	200,359	159,130	120	117	510	490	511	347
2019	1,667	1,124	224	1,445	150	137	202,844	161,104	126	122	545	524	547	371
2020	1,774	1,196	239	1,538	159	146	204,661	162,547	133	128	581	558	582	395
2021	1,757	1,185	236	1,523	158	144	199,229	158,233	129	124	575	553	577	391
2022	1,739	1,172	234	1,507	156	143	193,473	153,661	126	121	569	547	571	387
2023	1,719	1,159	231	1,490	154	141	187,355	148,802	123	117	562	541	564	383
2024	1,697	1,144	228	1,471	152	139	180,544	143,392	119	113	555	534	557	378
2025	1,665	1,122	224	1,443	149	137	173,428	137,741	115	109	545	524	546	371
2026	1,614	1,088	217	1,399	145	132	165,765	131,655	111	104	528	508	530	360
2027	1,564	1,054	210	1,356	140	128	153,071	121,572	106	99	512	492	513	348
Total:	19,588	13,204	2,633	16,977	1,758	1,607	2,249,216	1,786,383	1,434	1,376	6,409	6,161	6,429	4,364
Savings		**-6,384**		**14,344**		**-152**		**-462,832**		**-58**		**-249**		**-2,065**

Converting Mass Emissions to Concentrations

In this step the mass emissions were converted into emissions concentrations using a box model. The Box model calculates air changes for each city taking into account the width of the box area drawn over a city, its wind speed and mixing height.

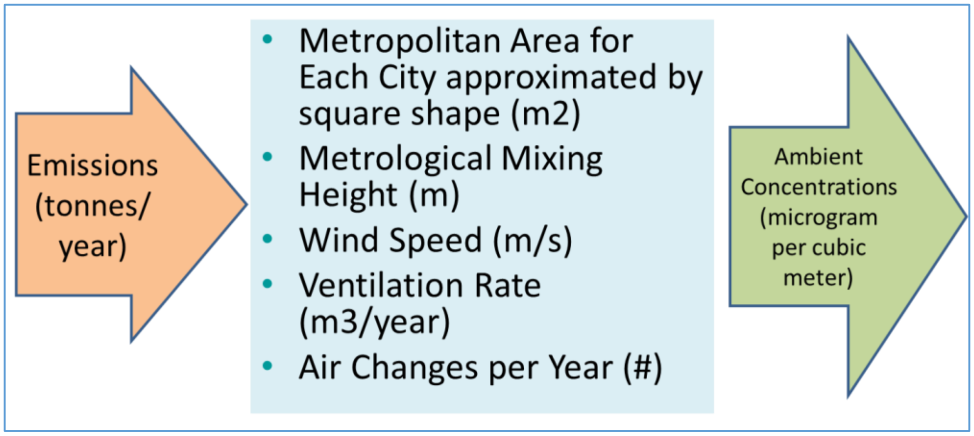


Figure 31: Box Model Flow Diagram

The images below show the box model boundaries.

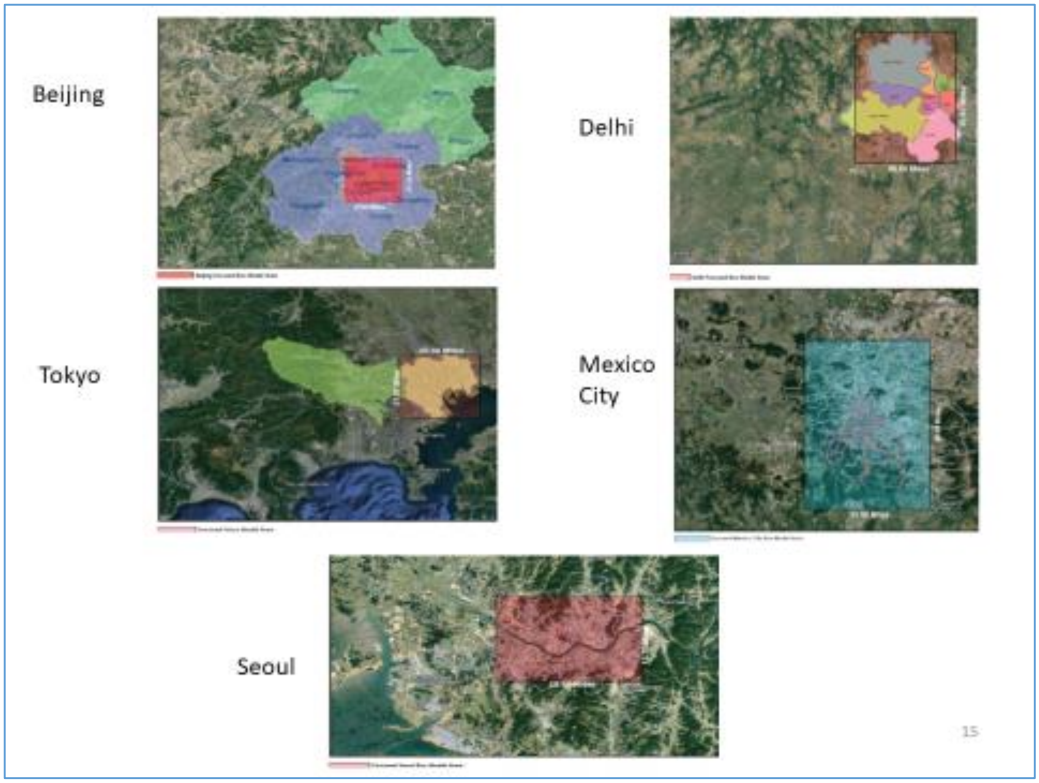


Figure 32: Box Model Boundaries for Each City

The metrological conditions and the shape of the box can significantly alter the relative emissions concentrations even in simple box models. As can be seen in the figure below 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.

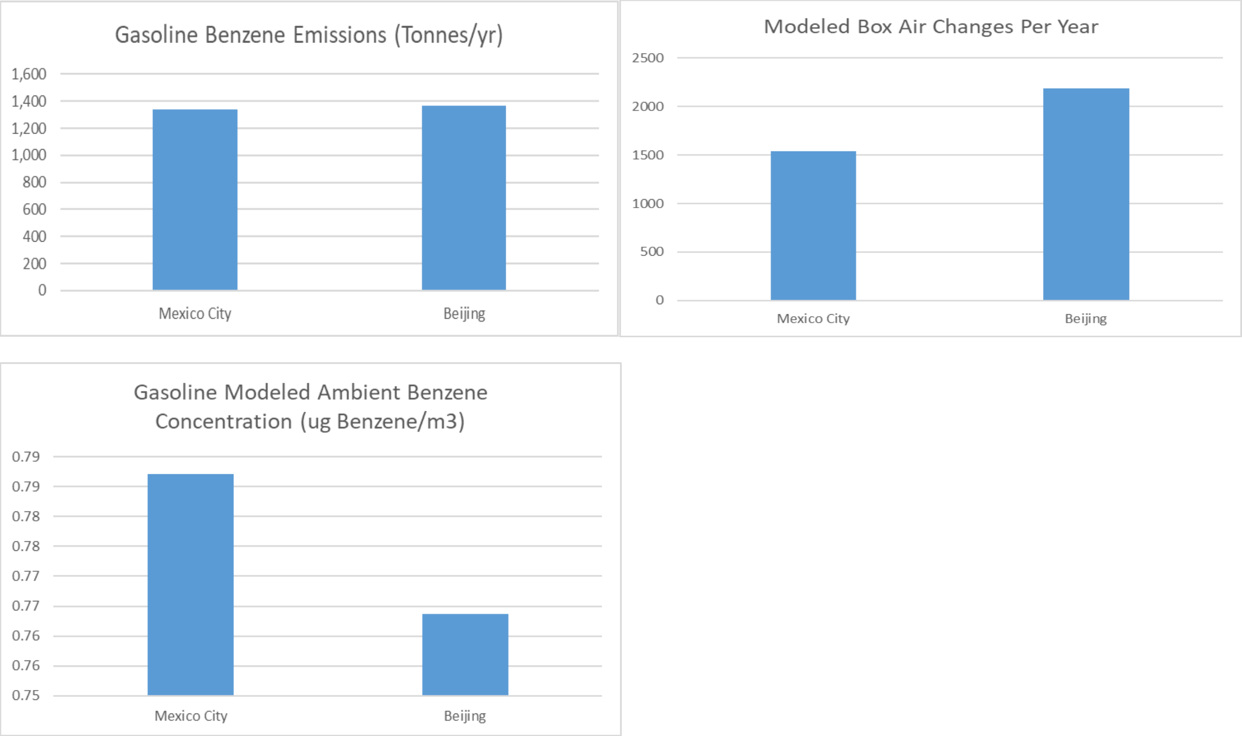


Figure 33: Box Model Relating Mass Emissions to Concentrations – Example Beijing

The box model provides a good approximation of concentrations. It should be noted that the 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. Also, we employed a conservatively adjusted mixing height based on Pendergast 1974 and Schubert 1976 who show that the temperature based assessments of the mixing height may overestimate the true mixing height. The reduction is consistent with the EPA Workbook of Atmospheric Dispersion Estimates (EPA, 1970): when most people in a densely populated urban area are surrounded by sources (streets) with some traffic volume, they are likely exposed to pollutants which haven't mixed to the full atmospheric mixing heights.

On the other hand, we did not take into account population growth within a city which given the growth of the studied cities will most certainly result in an underestimation of the derived health effects or exposure of particular occupational risk groups such as gasoline refueling station workers.

Pollutants Assessed for Health Impacts

Of the emissions affected by ethanol blended gasoline, several of the pollutants are well known to have adverse impacts on public health. In this study, the health impact of inhaling the following pollutants is considered:

Acetaldehyde. Acetaldehyde has been classified as *possibly carcinogenic to humans* (Group 2B) by the International Agency for Research on Cancer. The US EPA classifies acetaldehyde as a probable human carcinogen based on nasal and laryngeal tumors observed in rodents after inhalation exposure [48], [49].

Benzene. Benzene has been classified as *carcinogenic to humans* (Group 1) by the International Agency for Research on Cancer. Benzene causes acute myeloid leukemia (acute non-lymphocytic leukemia), and has been positively associated with acute lymphocytic leukemia, chronic lymphocytic leukemia, multiple myeloma and non-Hodgkin lymphoma [50], [51].

Benzo[a]pyrene (BaP). BaP has been classified as *carcinogenic to humans* (Group 1) by the International Agency for Research on Cancer. The basis for this classification is a clear mechanism of genotoxicity that impacts lung tumors, though epidemiologic studies have observed increased lung and skin cancer risks. Animal studies have observed cancers at many locations after exposure to BaP in mixtures through multiple routes. BaP is one of many polycyclic aromatic hydrocarbons (PAHs) emitted in vehicle exhaust, many of which are thought to be carcinogenic. For this analysis, BaP is used as an indicator of carcinogenic risk from PAHs because it is the most potent of the PAHs, and has been found to dominate the cancer risk posed by PAHs emitted by gasoline vehicles [52],[53],[54],[55].

Butadiene. 1,3-butadiene has been classified as *carcinogenic to humans* (Group 1) by the International Agency for Research on Cancer. 1,3-butadiene has been associated with cancer of the haematolymphatic organs, such as leukemia [56].

Carbon monoxide (CO). CO is an acute toxicant, and can result in unintentional vehicle-associated deaths, such as CO poisoning resulting from failures of the vehicle exhaust system. In general, ambient CO is not present at levels capable of causing CO poisoning, but acute exposures to ambient CO has been associated with increased mortality from cardiovascular disease, coronary heart disease and stroke [57], [58].

Fine Particulate Matter (PM). PM is a complex material, which may contain toxic heavy metals, PAHs, organic carbon, elemental carbon and other chemicals. The composition of PM varies geographically, in part due to fleet composition and fuels. Epidemiologic studies observe differences in the association between PM exposure and mortality, but it is not clear what drives geographical differences (e.g., PM composition, PM sources, topography, or other urban attributes). Inhalation of PM has been associated with a variety of health impacts that depend, in part, upon the duration and magnitude of exposures and the age of the population exposed. Herein we focus on mortality associated with chronic exposures, which is the outcome utilized by the US EPA risk assessment for long-term exposures to PM [59], [60].

Formaldehyde. Formaldehyde has been classified as *carcinogenic to humans* (Group 1) by the International Agency for Research on Cancer. There is scientific consensus that formaldehyde contributes to the development of cancer in the nasal tissues, though the association with lymphohematopoietic cancers is more controversial [61]; [62]; [63].

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

Cancer Outcomes and Impacts

The approach taken to estimate the impact of ethanol fuels on cancer outcomes is as follows. For each of the five cities, the airborne concentrations of the pollutants were estimated annually 2016-2027 for the three fuel scenarios (standard gasoline, E10 gasoline, and E20 gasoline). In general, the trend in airborne pollutant concentrations varies among years, and was not monotonic.

For each of 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 calculated 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 shift to ethanol fuel, and the reduction in inhalation exposure among the population. The approximate number of cancers avoided (or increased) by the change to ethanol fuel was then calculated 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. This calculation includes a number of assumptions that are not fully valid in this context, such as lifetime continuous inhalation exposure at the mean modeled values, but serves to provide an estimate of potential impact of ethanol fuel introduction.

The inhalation unit risk (IUR) factor is a standard metric for estimating excess lifetime cancer risk associated inhalation exposure, and assumes a lifetime of continuous exposure. The IUR factor has units of risk per 1 ug/m^3 inhalation exposure. The IUR factors used in this study are shown in the table below, and were derived by the California Office of Environmental Health Hazard Assessment (OEHHA). The OEHHA values were selected because they tend to be more health-conservative than values derived by the US EPA [64a].

For polycyclic aromatic hydrocarbons additional clarification is required. Vehicle exhaust contains a host of PAHs which are more or less carcinogenic. The carcinogenicity of BaP is well studied and toxic equivalency factors to characterize other PAHs have been developed [64b]. However, the overall cancer risk from PAHs is dominated by BaP for newer and older gasoline cars [64c]. Therefore, we followed the approach described in Bostrom et al [64c]: “in the past, EPA has assessed risks posed by mixtures of PAHs by assuming that all carcinogenic PAHs are as potent as benzo[a]pyrene (B[a]P), one of the most potent PAHs.” We also acknowledge the statement in Bostrom et al that this approach is likely overestimating the risk.

Table 40. Inhalation Unit Risk (IUR) factors for selected carcinogens in vehicle exhaust

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

The change in the number of cases of cancer estimated to result from the introduction of ethanol fuels relative to the continued use of gasoline is shown in the tables below. The emission for the "possibly known carcinogen in humans" acetaldehyde is estimated to increase with the use of ethanol fuels, resulting in an increase in the estimated number of associated cancers. For example, using E10 in Beijing may increase the lifetime cancer risk from associated increases in acetaldehyde emissions by 5.2 cases.

Table 41: Change in Cancer Cases for Acetaldehyde

Acetaldehyde	Change in Number of Cancer Cases
E10 Fuel	
Beijing	5.2
Delhi	3.9
Mexico City	11
Seoul	2.9
Tokyo	2.7
E20 Fuel	
Beijing	14
Delhi	11
Mexico City	28
Seoul	7.3
Tokyo	7.3

However, the increase from acetaldehyce cases is small relatively to the known carcinogens to humans including benzene, butadiene, benzopyrene/polycyclics, and formaldehyde (see figure below). Particularly noteworthy is the magnitude of the percent change in predicted cancer cases by pollutant. For example, adding ten percent ethanol by volume reduces benzene related cancers from gasoline vehicles in Delhi and Biejing by 27% and 23% respectively. Butadiene related cancer cases from gasoline in Delhi and Seoul can be reduced by 20% with the addition of ten percent ethanol and cut in half with the addition of twenty percent ethanol.

Table 42: Change in Number of Cancer Cases from Selected Air Toxins

	Change in Number of Cancer Cases by Pollutant				
	Acetaldehyde	**Benzene**	**Polycyclics**	**1,3-Butadiene**	**Formaldehyde**
E10 Fuel					
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 Fuel					
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

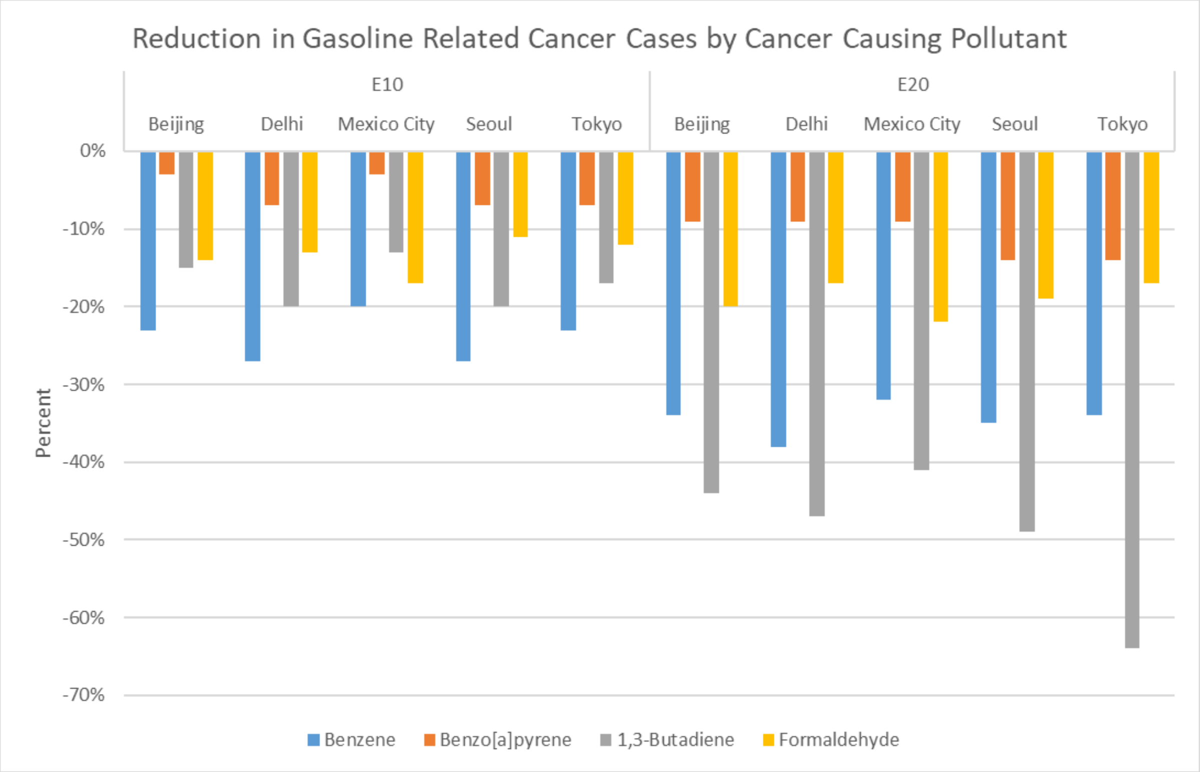


Figure: Reduction in Gasoline Related Cancer Cases by Pollutant

Cancer is a serious disease, and adversely impacts the quality and length of patient lives. Treatment of cancer incurs substantial healthcare costs, but has additional individual and social costs associated with diminished quality of life, such as lost income. To better characterize the impact to patients and society of the transition to ethanol fuels, we estimate the expected years of life lost and the direct healthcare costs associated with the change in the number of cancer cases. Years of life lost provide a summary measure of premature mortality. Potential years of life lost may be defined as the years of potential life lost due to premature deaths.

The carcinogenic pollutants considered in this study each cause a variety of cancers, each of which have different prognoses. The table below summarizes the years of potential life lost for the cancers relevant to the pollutants studied for the US population [65]. For each pollutant, the years of potential life lost owing to different types of cancers were averaged and applied to all cities. This simplification treats each type of cancer as equally likely, and the treatment/prognosis as uniform globally.

Table 43: Years of Potential Life Lost by Pollutant

	Benzene	**Acetaldehyde**	**Formaldehyde**	**Butadiene**	**Polycyclics**
leukemia	**15.6**			**15.6**	
lung and bronchus					**15.2**
non-Hodgkin lymphoma	14.0			14.0	
melanoma/ adenocarcinoma					
Melanoma		17.0	17.0		
Esophagus		16.2	16.2		16.2
Pancreas		15.1	15.1		
Prostate		10.0	10.0		
Myeloma	13.5				
Stomach				16.3	16.3
Hodgkin lymphoma				22.2	
Average	**14.4**	**14.6**	**14.6**	**17.0**	**15.9**

Ambient concentrations of acetaldehyde are estimated to increase with the transition to ethanol fuels, thus additional years of potential life will be lost. For all other pollutants, the transition to ethanol fuels is predicted to reduce ambient concentrations and the number of excess cancers, and thus save potential life lost relative to continued use of gasoline. In all cities, the transition to ethanol fuels is estimated to save thousands of years of potential life lost from exposure to these pollutants. In Mexico City, for example, the introduction of E10 will save over 5,000 years of life lost across the studied air toxins. In the US, a person-year of life lost has been valued at $150,000 which leads our assessment to show several hundred million dollars of savings from ethanol blends [73].

Table 44. Change in years of potential life lost or gained by pollutant.

	Acetal-dehyde	Benzene	Polycyclics/ Benzo[a]pyrene	Butadiene	Formal-dehyde	Total	Years of Life Value Saved
E10 Fuel							
Beijing	76	-1,135	-487	-1,667	-48	-3,262	-$489,246,266
Delhi	57	-1,375	-951	-1,835	-32	-4,136	-$620,409,006
Mexico City	154	-1,770	-692	-2,431	-138	-4,877	-$731,507,141
Seoul	43	-488	-641	-1,422	-20	-2,529	-$379,311,492
Tokyo	40	-566	-676	-1,303	-21	-2,527	-$379,052,100
E20							
Beijing	200	-1,671	-1,583	-4,894	-67	-8,015	-$1,202,226,527
Delhi	156	-1,967	-1,357	-4,286	-40	-7,494	-$1,124,045,017
Mexico City	401	-2,767	-1,521	-7,775	-182	-11,843	-$1,776,517,781
Seoul	106	-638	-1,259	-3,537	-35	-5,363	-$804,397,713
Tokyo	106	-828	-1,486	-4,918	-30	-7,155	-$1,073,306,075

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

Cancer treatment incurs substantial costs of the healthcare system, but these costs are only part of the total costs of cancer. A recent study shows that among national cost in the United States female breast was the cancer site with the highest cost in 2010 ($16.50 billion) followed by colorectal ($14.14 billion), lymphoma ($12.14 billion), lung ($12.12 billion), and prostate ($11.85 billion). Of particular interest in our study are lymphocytic and lung cancers [66].

We were not able to identify standardized global data about the individual costs of treatment for cancers, though it is clear that treatment costs vary widely among cancers and countries. Consider leukemia, which has one of the most expensive cancer treatment costs. In New Zealand, total treatment costs for leukemia and non-Hodgkin lymphoma are approximately $95,000 and $72,000, respectively [67]. In the United Kingdom, treatment costs for leukemia are approximately $70,000 (£43,109) [68].

Treatment costs are typically higher in the US, where treatment costs for the last year of life alone are approximately $195,000 [69]. Data from the National Cancer Institute shows Last Year of Life treatment costs alone for leukemia total $195,196 (year 2010 basis). Treatment for acute myeloid leukemia involving stem cell transplant and chemotherapy costs more than $540,000, on average [70]. Treatment cost for lung cancers also vary widely and can approximate those of leukemia especially during the initial treatment phase after diagnosis (often assessed separately relative to continuing care and last year of life phase of care) [71]. Given that the pollutants considered in this study predominantly cause lymphohematopoietic and lung cancers, and that treatment costs in developing countries are likely low relative to costs in the US, we assumed that each cancer case required $70,000 in treatment costs.

Ambient concentrations of acetaldehyde are estimated to increase with the transition to ethanol fuels, thus additional cancers and additional treatment costs are expected (see table below). For all other pollutants, the transition to ethanol fuels is predicted to reduce ambient concentrations and the number of excess cancers, and thus save treatment costs relative to continued use of gasoline. In all cities, the transition to ethanol fuels is estimated to save millions of dollars in cancer treatment costs to the healthcare system. For example, using E10 in Mexico City will likely decrease health care cost by $23 million across the studied air toxins.

Table 45. Change in cancer treatment costs (thousands of dollars) to the healthcare system by pollutant.

		Acetaldehyde	**Benzene**	**Polycyclics/ Benzo[a]pyrene**	**1,3- Butadiene**	**Formaldehyde**
	E10 Fuel					
	Beijing	$367,056	-$5,532,297	-$2,145,093	-$6,854,602	-$231,735
	Delhi	$272,476	-$6,701,673	-$4,185,756	-$7,544,755	-$151,757
	Mexico City	$738,203	-$8,622,903	-$3,047,558	-$9,993,893	-$661,731
	Seoul	$204,229	-$2,375,488	-$2,821,579	-$5,848,254	-$98,195
	Tokyo	$192,256	-$2,759,586	-$2,976,347	-$5,358,432	-$102,630
			E20			
	Beijing	$959,188	-$8,140,585	-$6,971,273	-$20,120,556	-$320,442
	Delhi	$749,673	-$9,582,473	-$5,974,581	-$17,621,264	-$193,124
	Mexico City	$1,927,411	-$13,481,065	-$6,696,530	-$31,968,450	-$872,589
	Seoul	$510,147	-$3,107,325	-$5,543,671	-$14,541,445	-$169,236
	Tokyo	$510,728	-$4,033,351	-$6,540,055	-$20,221,907	-$144,726

Note: Negative values indicate a savings in healthcare costs.

Non-Cancer Outcomes

Components of vehicle exhaust contribute to a variety of non-cancer health outcomes. We considered two agents, PM and CO, as emissions of these were part of our mass emissions assessment.

The PM concentrations estimated in this analysis are specific to gasoline vehicles, and thus represent only one of many sources of PM in urban areas. Furthermore, emissions savings from ethanol blends in this study are only associated with the increasing share of gasoline direct injection engines as outlined in previous chapters. During the last 3 years of the study horizon when GDI engines are the dominant power train we show that the introduction of E20 fuels in particular could yield savings in heart failure cases and percent reductions in heart failure from gasoline related PM emissions.

Table 46: Particulate Matter Change in Heart Failure Cases

	Change in Number of Heart Failure Cases (% Change) for PM
Beijing	-8.8 (-11%)
Delhi	-11.2 (-6.1%)
Mexico City	-2.8 (-4.9%)
Seoul	-4.5 (-7.7%)
Tokyo	-7.5 (-6)

Ambient PM concentrations change from day-to-day, and these acute exposures have also been associated with a variety of adverse health outcomes, such a heart failure, but these exposure-response relationships have not been considered in this analysis because the models predict annual average exposures, rather than daily exposures [58].

Exposure CO causes acute intoxication, which can result in death. From 1968 to 1998 the crude death rate from unintentional motor vehicle-related CO poisoning decreased from 3.86 per 1 million person-years to 0.88 per 1 million person years, with the reduction attributed, in part, to reduction in CO emissions from motor vehicles [72]. From these data, we determined that 1.8 deaths per year are associated with the emission of 1 g CO per mile. In this study, we estimated CO emission reduced by 0.1-0.2 g/mile with the use E10 fuel and 0.4-0.9 g/mile with the use of E20 fuel relative to continued use of gasoline. These reductions would be associated with preventing 0-2 deaths annually, in each city.

14.2 Summary of the Health Impact Assessment

This chapter of the 5 Cities Study assessed the health impact of ethanol blended gasoline. The introduction of ethanol fuels was estimated to yield a net reduction of approximately 200-300 cancers per city, associated with several of the key pollutants in vehicle exhaust relative to continued use in gasoline, and varying among cities and between ethanol fuel blends. Avoiding these cancers will save several thousand years of potential life lost in each city and an additional tens of millions of dollars of direct healthcare costs for cancer treatment.

The impact of cancer, however, is much greater than these metrics, as cancer adversely impacts the quality of life, can lead to loss of income, and devastates families. For example, in the US, a person-year of life lost has been valued at $150,000 which leads our assessment to show several hundred million dollars of savings from ethanol blends [73].

For context, other regulatory actions have been taken to prevent numbers of cancers that seem modest relative to the total burden of disease. For example, in the reduction of the Permissible Exposure Limit for 1,3-butadiene in the United States to 1 ppm was estimated by the Occupational Safety and Health Administration to avoid 59 cancers among approximately 9000 exposed workers over a working lifetime of 45 years, or 1.3 cancers per year [74]. Costs to employers to comply with the new 1,3-butadiene standard was estimated to be $2.9 million in 1996 dollars annually, or approximately $2.3 million per cancer avoided per year. Similarly, the reduction in the Permissible Exposure Limit for benzene from 10 ppm to 1 ppm was estimated by the Occupational Safety and Health Administration to avoid 326 deaths from leukemia and other lymphohematopoietic cancers over 45 years, or 7.2 cancers per year; a reduction of similar magnitude to the presented ethanol blended gasoline efforts. [75]. Costs to employers to comply with the new benzene standard was estimated to be $24 million in 1986 dollars annually, or $3.3 million per cancer avoided per year.

The health benefit of transitioning to ethanol fuels in these five cities is quantifiable and significant relative to the total burden of disease within the context that gasoline vehicle exhaust is one of many contributors to air pollution. The results of the study suggest that transition to ethanol fuels will benefit public health.

15 Update: Korea Gasoline Resampling

Our original fuel samples for Seoul did not show any MTBE content in the fuel. We learned that only a relatively small supply that may not be representative of fuels sold into the Seoul market may in fact not contain MTBE. Therefore, we resampled three gasoline stations and the resampled stations showed MTBE content in their fuel ranging from 5.4 vol % to 11.6 vol % with a mean of 10 vol%. Directionally, the higher MTBE content in the sampled fuel will reduce the tailpipe emissions savings expected from ethanol blends but increase the GHG emissions savings. This is due to the fact that ethanol will mostly substitute for MTBE in the finished fuel.

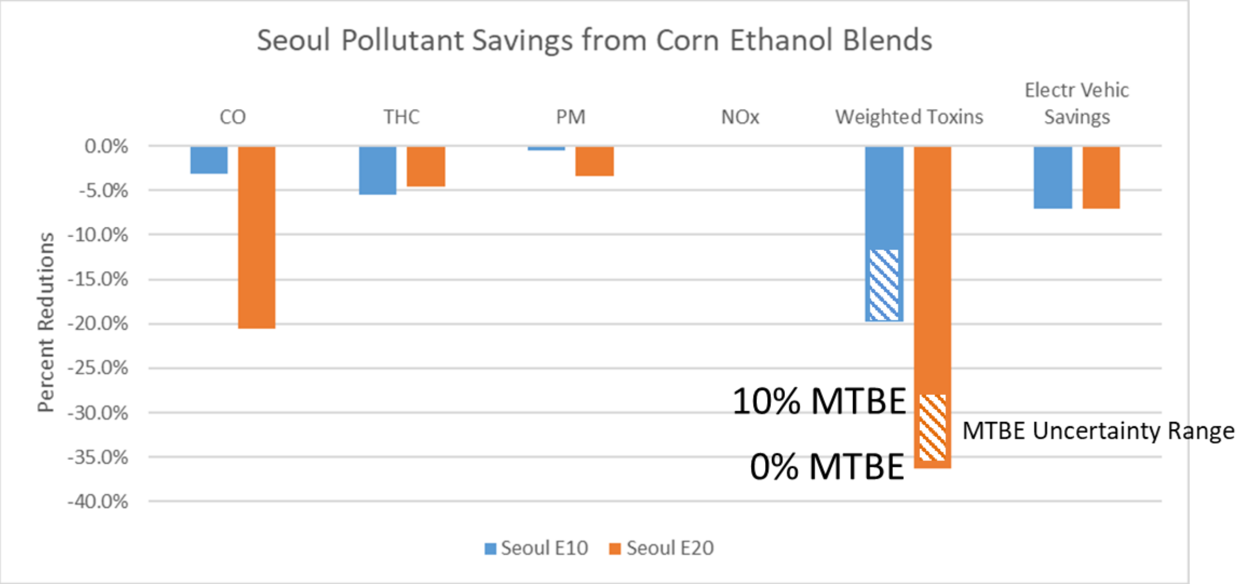


Figure 34: Tailpipe Emissions Adjustments for Seoul

The updated GHG emissions savings reflecting 10% MTBE are show below.

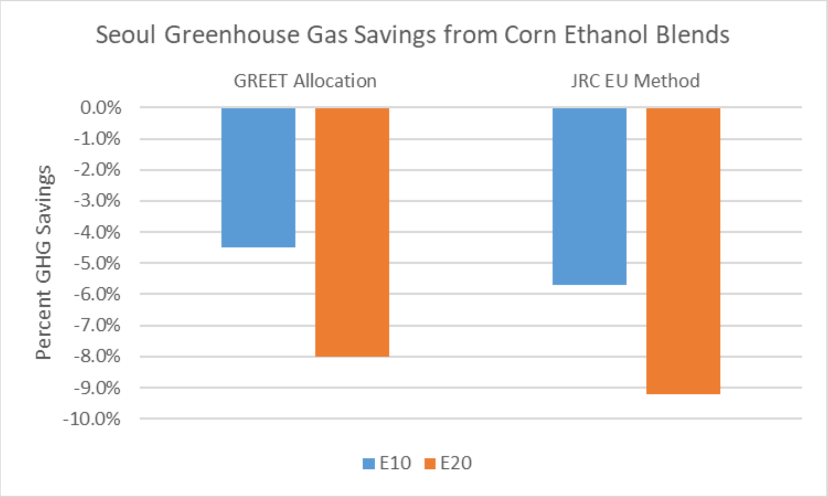


Figure 35: GHG Emissions Adjustments with 10% MTBE for Seoul

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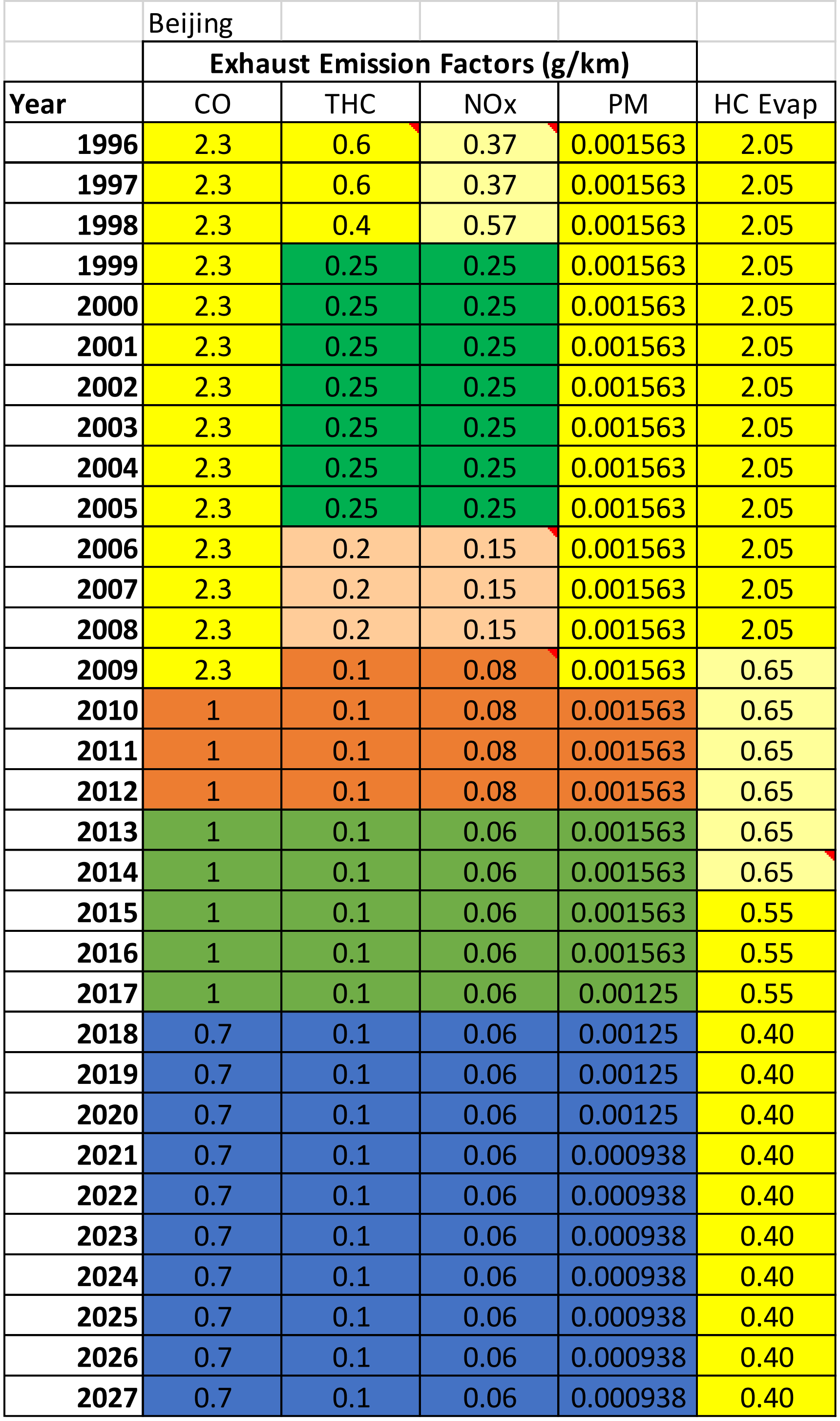
[73] KR Yabroff, CJ Bradley, AB Mariotto, ML Brown and EJ Feuer. Estimates and projections of value of life lost from cancer deaths in the United States. J Natl Cancer Inst 100(24): 1755-1762.

[74] Occupational Exposure to 1,3-butadiene. Final Rule. Federal Register 61: 56746-56856. (1996).

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

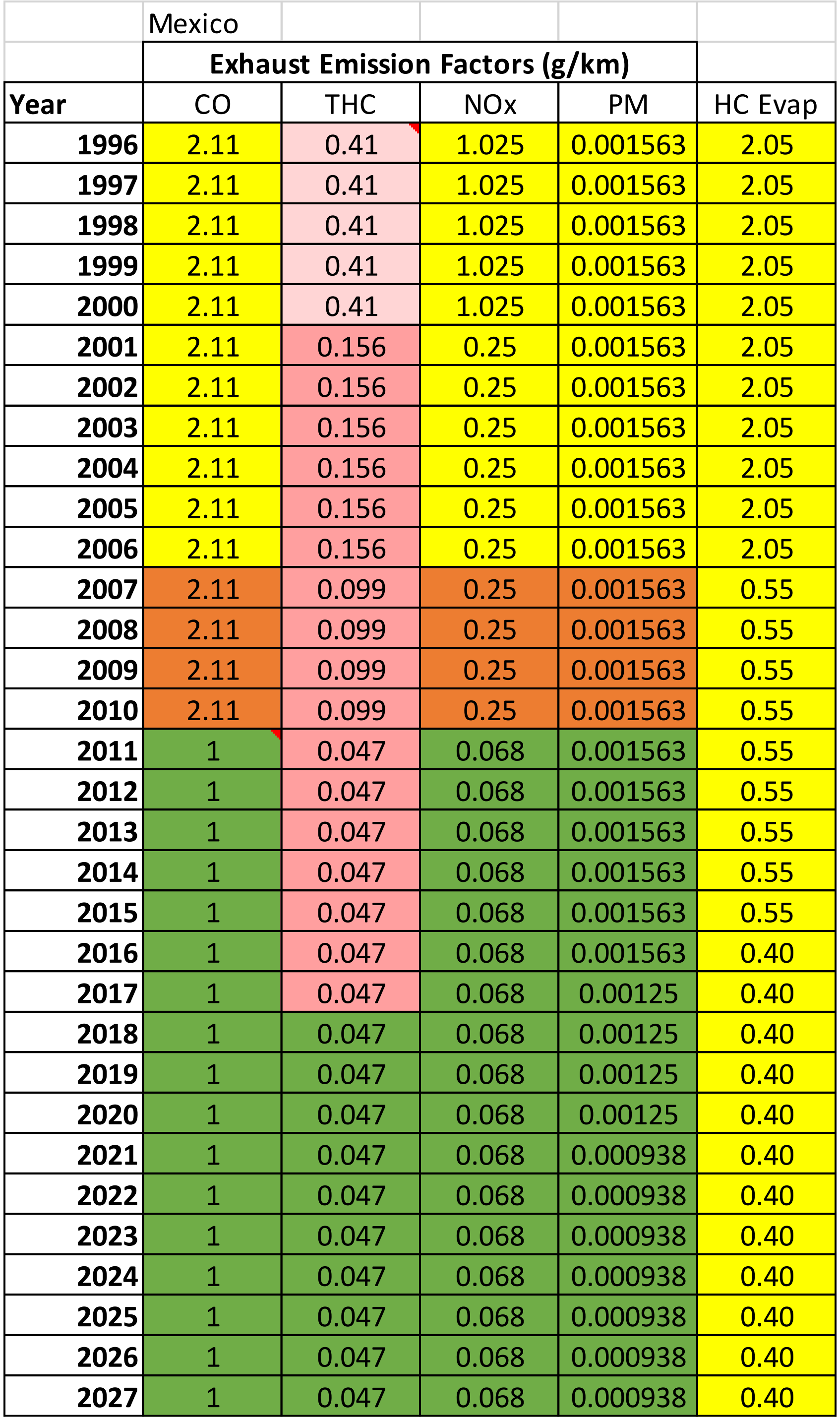
Appendix A: Emissions Standards by City

Table 47: Emissions Standards Beijing



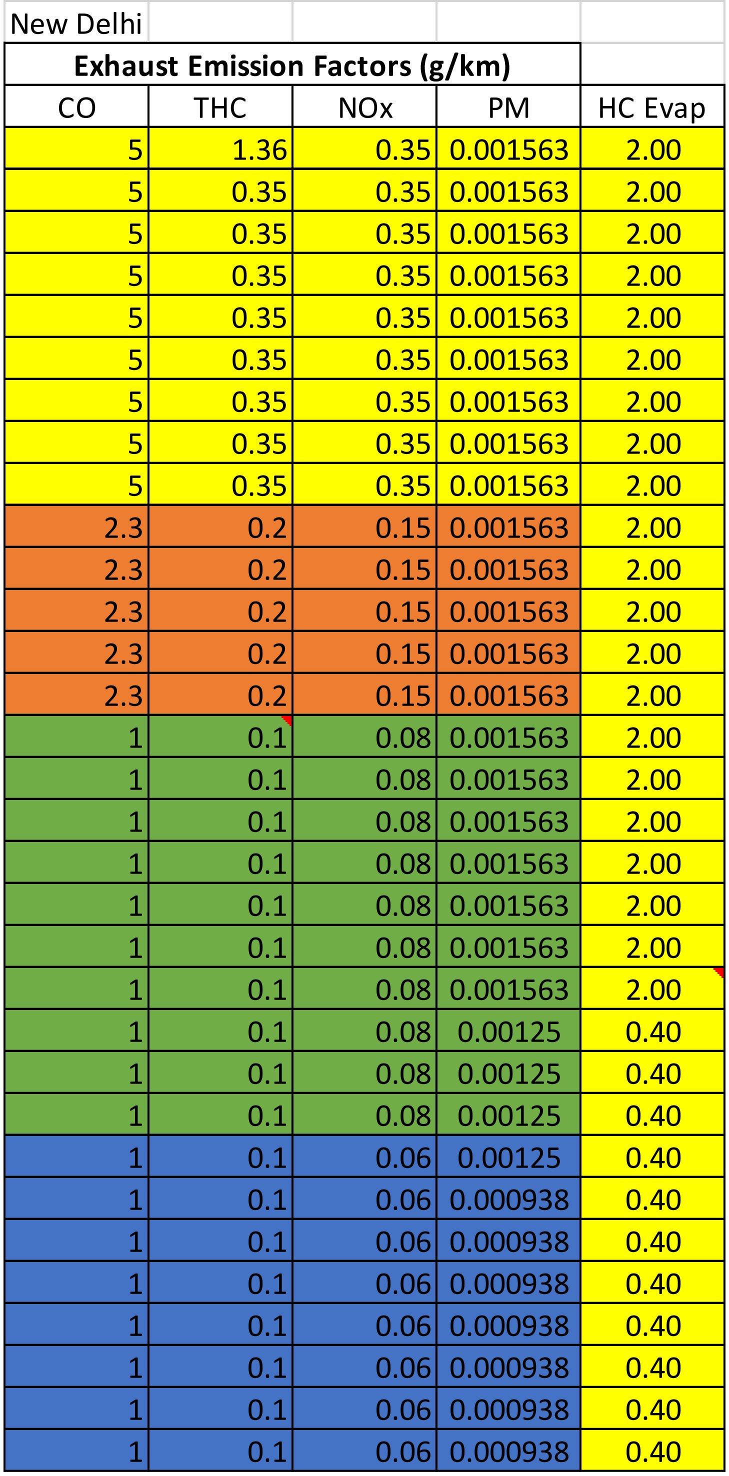
	Beijing				
	Exhaust Emission Factors (g/km)				
Year	CO	THC	NOx	PM	HC Evap
1996	2.3	0.6	0.37	0.001563	2.05
1997	2.3	0.6	0.37	0.001563	2.05
1998	2.3	0.4	0.57	0.001563	2.05
1999	2.3	0.25	0.25	0.001563	2.05
2000	2.3	0.25	0.25	0.001563	2.05
2001	2.3	0.25	0.25	0.001563	2.05
2002	2.3	0.25	0.25	0.001563	2.05
2003	2.3	0.25	0.25	0.001563	2.05
2004	2.3	0.25	0.25	0.001563	2.05
2005	2.3	0.25	0.25	0.001563	2.05
2006	2.3	0.2	0.15	0.001563	2.05
2007	2.3	0.2	0.15	0.001563	2.05
2008	2.3	0.2	0.15	0.001563	2.05
2009	2.3	0.1	0.08	0.001563	0.65
2010	1	0.1	0.08	0.001563	0.65
2011	1	0.1	0.08	0.001563	0.65
2012	1	0.1	0.08	0.001563	0.65
2013	1	0.1	0.06	0.001563	0.65
2014	1	0.1	0.06	0.001563	0.65
2015	1	0.1	0.06	0.001563	0.55
2016	1	0.1	0.06	0.001563	0.55
2017	1	0.1	0.06	0.00125	0.55
2018	0.7	0.1	0.06	0.00125	0.40
2019	0.7	0.1	0.06	0.00125	0.40
2020	0.7	0.1	0.06	0.00125	0.40
2021	0.7	0.1	0.06	0.000938	0.40
2022	0.7	0.1	0.06	0.000938	0.40
2023	0.7	0.1	0.06	0.000938	0.40
2024	0.7	0.1	0.06	0.000938	0.40
2025	0.7	0.1	0.06	0.000938	0.40
2026	0.7	0.1	0.06	0.000938	0.40
2027	0.7	0.1	0.06	0.000938	0.40

Table 48: Emissions Standards Mexico City



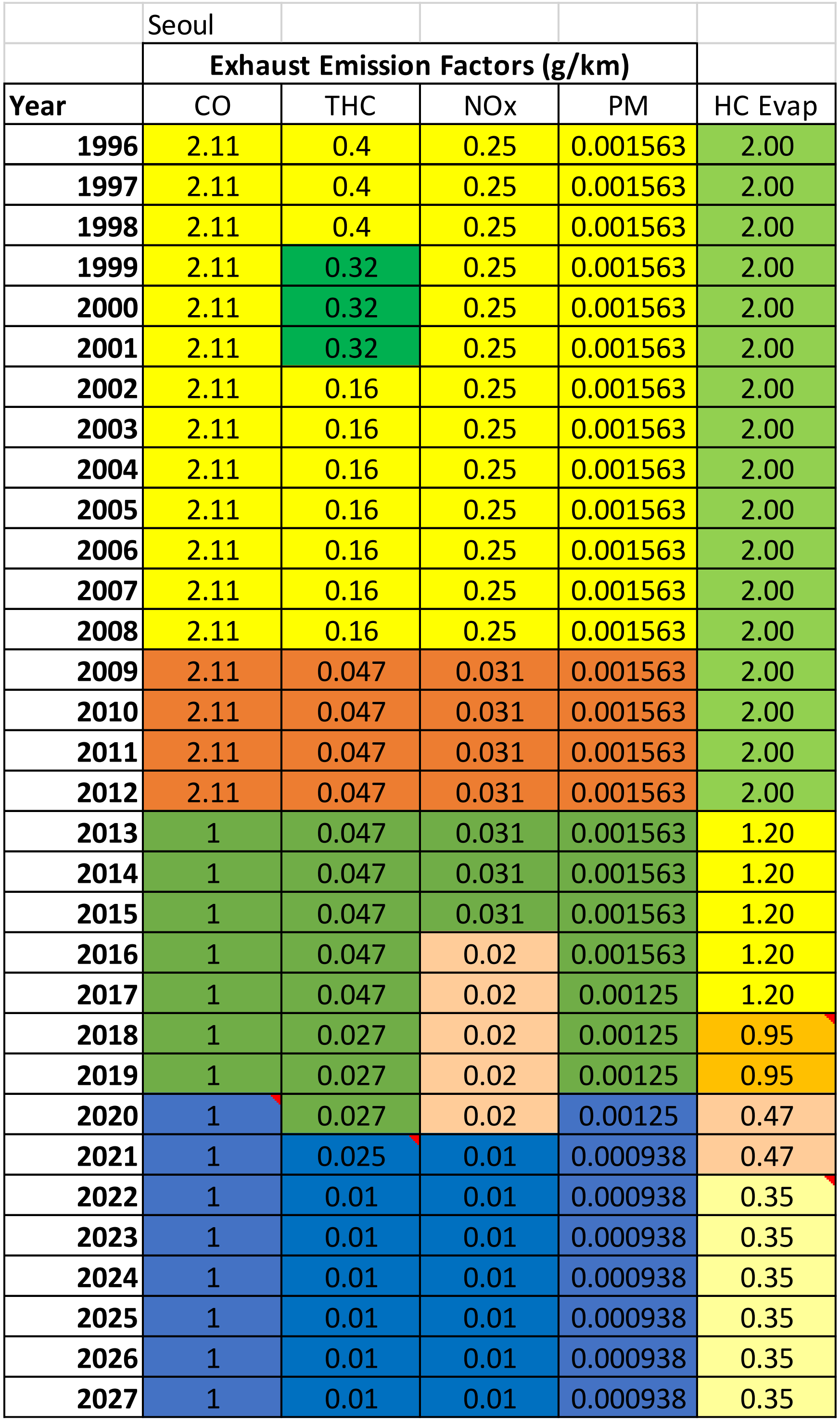
	Mexico				
	Exhaust Emission Factors (g/km)				
Year	CO	THC	NOx	PM	HC Evap
1996	2.11	0.41	1.025	0.001563	2.05
1997	2.11	0.41	1.025	0.001563	2.05
1998	2.11	0.41	1.025	0.001563	2.05
1999	2.11	0.41	1.025	0.001563	2.05
2000	2.11	0.41	1.025	0.001563	2.05
2001	2.11	0.156	0.25	0.001563	2.05
2002	2.11	0.156	0.25	0.001563	2.05
2003	2.11	0.156	0.25	0.001563	2.05
2004	2.11	0.156	0.25	0.001563	2.05
2005	2.11	0.156	0.25	0.001563	2.05
2006	2.11	0.156	0.25	0.001563	2.05
2007	2.11	0.099	0.25	0.001563	0.55
2008	2.11	0.099	0.25	0.001563	0.55
2009	2.11	0.099	0.25	0.001563	0.55
2010	2.11	0.099	0.25	0.001563	0.55
2011	1	0.047	0.068	0.001563	0.55
2012	1	0.047	0.068	0.001563	0.55
2013	1	0.047	0.068	0.001563	0.55
2014	1	0.047	0.068	0.001563	0.55
2015	1	0.047	0.068	0.001563	0.55
2016	1	0.047	0.068	0.001563	0.40
2017	1	0.047	0.068	0.00125	0.40
2018	1	0.047	0.068	0.00125	0.40
2019	1	0.047	0.068	0.00125	0.40
2020	1	0.047	0.068	0.00125	0.40
2021	1	0.047	0.068	0.000938	0.40
2022	1	0.047	0.068	0.000938	0.40
2023	1	0.047	0.068	0.000938	0.40
2024	1	0.047	0.068	0.000938	0.40
2025	1	0.047	0.068	0.000938	0.40
2026	1	0.047	0.068	0.000938	0.40
2027	1	0.047	0.068	0.000938	0.40

Table 49: Emissions Standards New Delhi



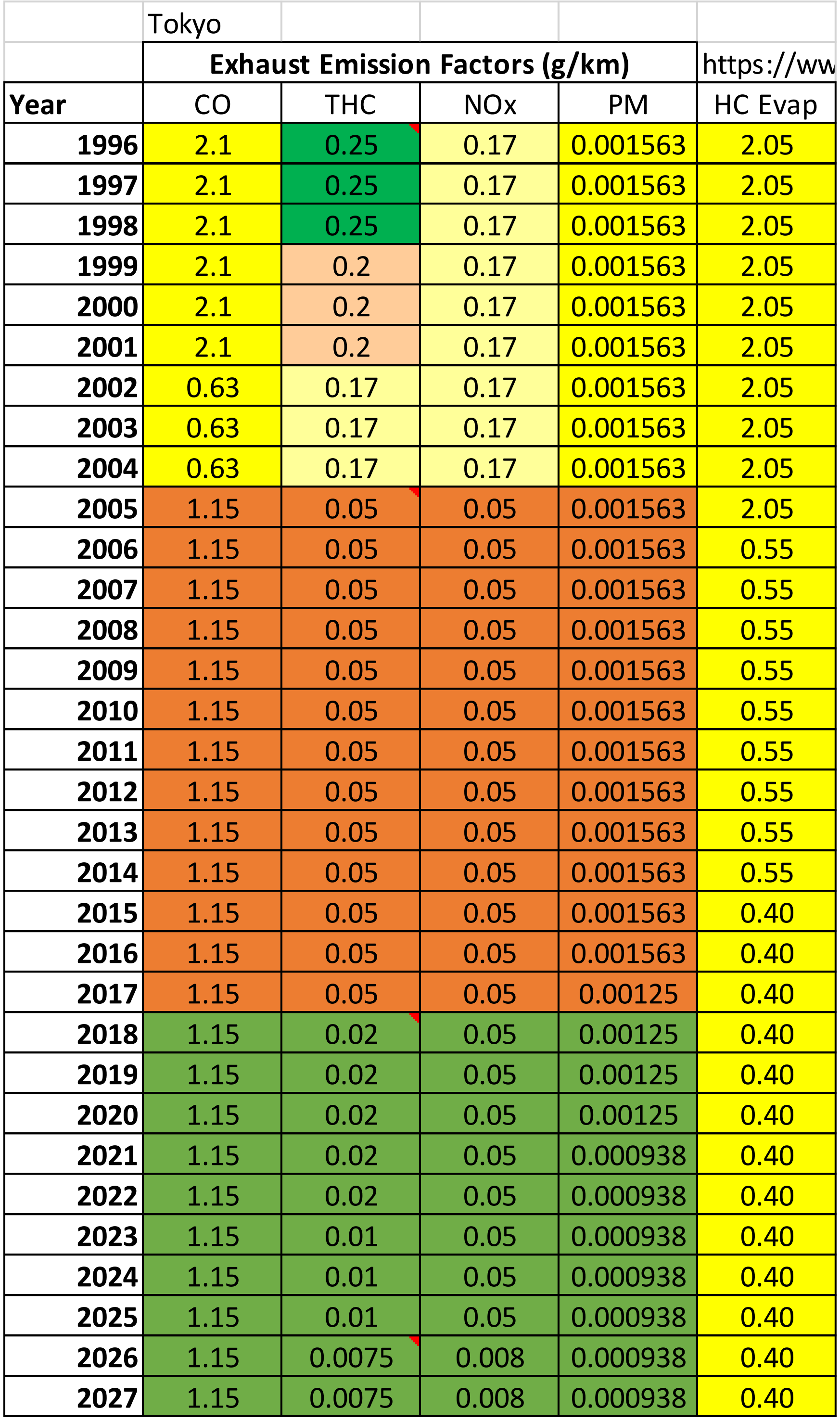
New Delhi				
Exhaust Emission Factors (g/km)				
CO	THC	NOx	PM	HC Evap
5	1.36	0.35	0.001563	2.00
5	0.35	0.35	0.001563	2.00
5	0.35	0.35	0.001563	2.00
5	0.35	0.35	0.001563	2.00
5	0.35	0.35	0.001563	2.00
5	0.35	0.35	0.001563	2.00
5	0.35	0.35	0.001563	2.00
5	0.35	0.35	0.001563	2.00
5	0.35	0.35	0.001563	2.00
2.3	0.2	0.15	0.001563	2.00
2.3	0.2	0.15	0.001563	2.00
2.3	0.2	0.15	0.001563	2.00
2.3	0.2	0.15	0.001563	2.00
2.3	0.2	0.15	0.001563	2.00
1	0.1	0.08	0.001563	2.00
1	0.1	0.08	0.001563	2.00
1	0.1	0.08	0.001563	2.00
1	0.1	0.08	0.001563	2.00
1	0.1	0.08	0.001563	2.00
1	0.1	0.08	0.001563	2.00
1	0.1	0.08	0.001563	2.00
1	0.1	0.08	0.00125	0.40
1	0.1	0.08	0.00125	0.40
1	0.1	0.08	0.00125	0.40
1	0.1	0.06	0.00125	0.40
1	0.1	0.06	0.000938	0.40
1	0.1	0.06	0.000938	0.40
1	0.1	0.06	0.000938	0.40
1	0.1	0.06	0.000938	0.40
1	0.1	0.06	0.000938	0.40
1	0.1	0.06	0.000938	0.40
1	0.1	0.06	0.000938	0.40

Table 50: Emissions Standards Seoul



	Seoul				
	Exhaust Emission Factors (g/km)				
Year	CO	THC	NOx	PM	HC Evap
1996	2.11	0.4	0.25	0.001563	2.00
1997	2.11	0.4	0.25	0.001563	2.00
1998	2.11	0.4	0.25	0.001563	2.00
1999	2.11	0.32	0.25	0.001563	2.00
2000	2.11	0.32	0.25	0.001563	2.00
2001	2.11	0.32	0.25	0.001563	2.00
2002	2.11	0.16	0.25	0.001563	2.00
2003	2.11	0.16	0.25	0.001563	2.00
2004	2.11	0.16	0.25	0.001563	2.00
2005	2.11	0.16	0.25	0.001563	2.00
2006	2.11	0.16	0.25	0.001563	2.00
2007	2.11	0.16	0.25	0.001563	2.00
2008	2.11	0.16	0.25	0.001563	2.00
2009	2.11	0.047	0.031	0.001563	2.00
2010	2.11	0.047	0.031	0.001563	2.00
2011	2.11	0.047	0.031	0.001563	2.00
2012	2.11	0.047	0.031	0.001563	2.00
2013	1	0.047	0.031	0.001563	1.20
2014	1	0.047	0.031	0.001563	1.20
2015	1	0.047	0.031	0.001563	1.20
2016	1	0.047	0.02	0.001563	1.20
2017	1	0.047	0.02	0.00125	1.20
2018	1	0.027	0.02	0.00125	0.95
2019	1	0.027	0.02	0.00125	0.95
2020	1	0.027	0.02	0.00125	0.47
2021	1	0.025	0.01	0.000938	0.47
2022	1	0.01	0.01	0.000938	0.35
2023	1	0.01	0.01	0.000938	0.35
2024	1	0.01	0.01	0.000938	0.35
2025	1	0.01	0.01	0.000938	0.35
2026	1	0.01	0.01	0.000938	0.35
2027	1	0.01	0.01	0.000938	0.35

Table 51*: Emissions Standards Japan*



	Tokyo				
	Exhaust Emission Factors (g/km)				https://ww
Year	CO	THC	NOx	PM	HC Evap
1996	2.1	0.25	0.17	0.001563	2.05
1997	2.1	0.25	0.17	0.001563	2.05
1998	2.1	0.25	0.17	0.001563	2.05
1999	2.1	0.2	0.17	0.001563	2.05
2000	2.1	0.2	0.17	0.001563	2.05
2001	2.1	0.2	0.17	0.001563	2.05
2002	0.63	0.17	0.17	0.001563	2.05
2003	0.63	0.17	0.17	0.001563	2.05
2004	0.63	0.17	0.17	0.001563	2.05
2005	1.15	0.05	0.05	0.001563	2.05
2006	1.15	0.05	0.05	0.001563	0.55
2007	1.15	0.05	0.05	0.001563	0.55
2008	1.15	0.05	0.05	0.001563	0.55
2009	1.15	0.05	0.05	0.001563	0.55
2010	1.15	0.05	0.05	0.001563	0.55
2011	1.15	0.05	0.05	0.001563	0.55
2012	1.15	0.05	0.05	0.001563	0.55
2013	1.15	0.05	0.05	0.001563	0.55
2014	1.15	0.05	0.05	0.001563	0.55
2015	1.15	0.05	0.05	0.001563	0.40
2016	1.15	0.05	0.05	0.001563	0.40
2017	1.15	0.05	0.05	0.00125	0.40
2018	1.15	0.02	0.05	0.00125	0.40
2019	1.15	0.02	0.05	0.00125	0.40
2020	1.15	0.02	0.05	0.00125	0.40
2021	1.15	0.02	0.05	0.000938	0.40
2022	1.15	0.02	0.05	0.000938	0.40
2023	1.15	0.01	0.05	0.000938	0.40
2024	1.15	0.01	0.05	0.000938	0.40
2025	1.15	0.01	0.05	0.000938	0.40
2026	1.15	0.0075	0.008	0.000938	0.40
2027	1.15	0.0075	0.008	0.000938	0.40

Appendix B: iBEAM (2017) Module 1 Interface Summary

The International Biofuels Emissions Analysis Model (iBEAM) was developed to calculate emissions from different air emissions pollutants in major global cities. The model structure allows users to choose from different scenarios or add scenarios that are deemed appropriate. The model structure also provides a structure that can be easily expanded to other cities in the future.

Currently, iBEAM is populated with data for five cities including Beijing, Seoul, Tokyo, New Delhi, and Mexico City.

Input+Output Worksheet – Left Section

- When clicking on the rose-colored cells in this tab a drop down menu appears that enables a selection of the options listed in the table right below that cell.
- Inputs 1a and 1b allow to select the city and ethanol blend of interest.
- Inputs 2a and 2b allow the selection of the end point of EV shares and GDI penetration by 2027.
- Input 3 allows to select between “average” and the more conservative “curve fit” emissions adjustments by vehicle age.
- Input 4 enables advanced users to change the efficiency and assumed evaporative emissions control technology adoption by city.
- Input 5 pertains to greenhouse gas modeling and allows the users to change between models and allocation methods as well as consideration of optional CO_2 recovery at the plant level.
- Finally, a table of the relative potency of toxic air contaminants is provided on this sheet.

Input+Output Worksheet – Right Section

The right section of this tab references and displays the summary findings for the scenarios selected in the left section. It displays the number of projected vehicles, their projected fuel use, the respective fuel economy and vehicle distances travelled. Just below the modeled emissions results are displayed for gasoline, E10, and E20 blends.

Individual City Worksheets

A total of 13 worksheets contain the databases and calculations behind the emissions assessments. The worksheet tabs contain the following information:

Description	**Sheet**	Protected
Enables Selection of City and Biofuels Emissions Scenario	**InputOutput**	No
Greenhouse Gas Calculations	**GHG**	Yes
Emission Calculations for all Cities	**EmissCacs**	Yes
Vehicle Roll-In Calculations based on Population and Vehicle Retirement	**VehMatrix**	Yes
Evaporative Emissions Data and Calculations	**EVAP**	Yes
Ethanol Emissions Factors and Fuel Effects	**EthanolFact**	Yes
Complex Model Factors and City Specific Blending Results	**ComplexFact**	Yes
Beijing Vehicle and Gasoline Factors	**BV**	No
Mexico City Vehicle and Gasoline Factors	**MV**	No
New Delhi Vehicle and Gasoline Factors	**NV**	No
Seoul Vehicle Data and Gasoline Factors	**SV**	No
Tokyo Vehicle Data and Gasoline Factors	**TV**	No
Graphs and Tables for City to City Comparisons	**Standards**	No

Appendix C: European Union RED Reference

Note: ISCC is one of the most commonly used certification protocols recognized by the EU

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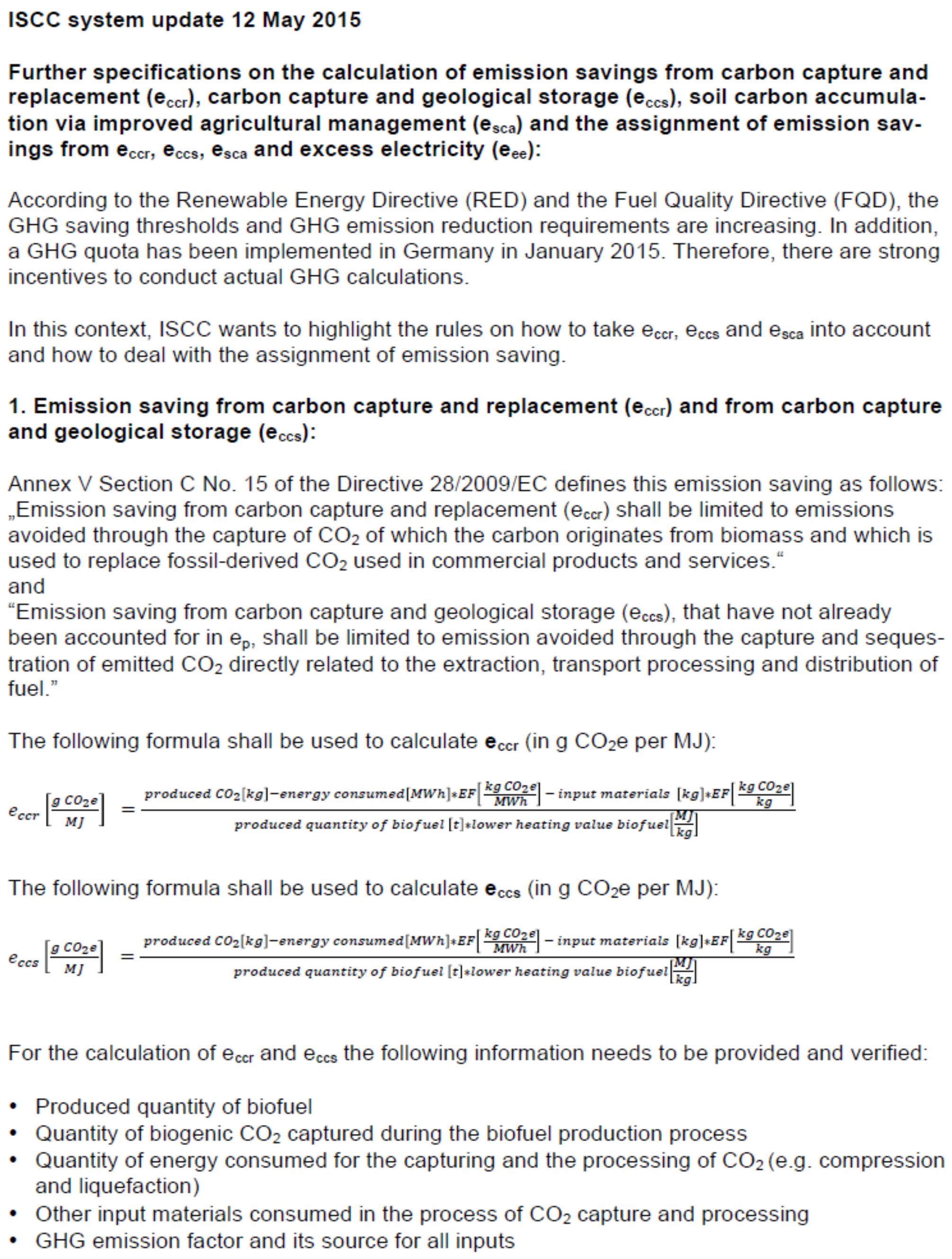


ISCC system update 12 May 2015

Further specifications on the calculation of emission savings from carbon capture and replacement (e_{ccr}), carbon capture and geological storage (e_{ccs}), soil carbon accumulation via improved agricultural management (e_{sca}) and the assignment of emission savings from e_{ccr}, e_{ccs}, e_{sca} and excess electricity (e_{ee}):

According to the Renewable Energy Directive (RED) and the Fuel Quality Directive (FQD), the GHG saving thresholds and GHG emission reduction requirements are increasing. In addition, a GHG quota has been implemented in Germany in January 2015. Therefore, there are strong incentives to conduct actual GHG calculations.

In this context, ISCC wants to highlight the rules on how to take e_{ccr}, e_{ccs} and e_{sca} into account and how to deal with the assignment of emission saving.

1. Emission saving from carbon capture and replacement (e_{ccr}) and from carbon capture and geological storage (e_{ccs}):

Annex V Section C No. 15 of the Directive 28/2009/EC defines this emission saving as follows:
„Emission saving from carbon capture and replacement (e_{ccr}) shall be limited to emissions avoided through the capture of CO_2 of which the carbon originates from biomass and which is used to replace fossil-derived CO_2 used in commercial products and services."
and
"Emission saving from carbon capture and geological storage (e_{ccs}), that have not already been accounted for in e_p, shall be limited to emission avoided through the capture and sequestration of emitted CO_2 directly related to the extraction, transport processing and distribution of fuel."

The following formula shall be used to calculate e_{ccr} (in g CO_2e per MJ):

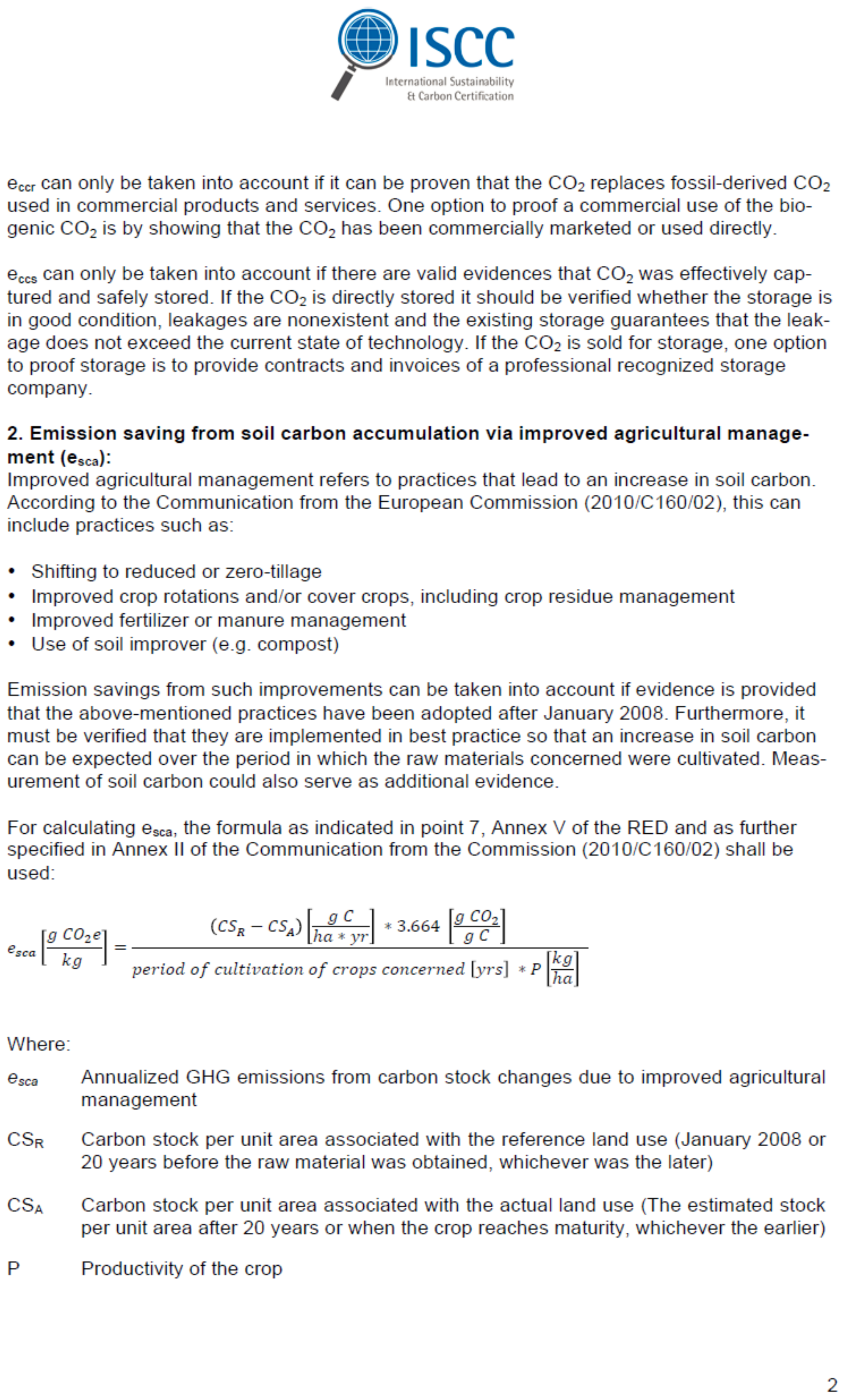
$$e_{ccr}\left[\frac{g\ CO_2e}{MJ}\right] = \frac{produced\ CO_2[kg] - energy\ consumed[MWh] * EF\left[\frac{kg\ CO_2e}{MWh}\right] - input\ materials\ [kg] * EF\left[\frac{kg\ CO_2e}{kg}\right]}{produced\ quantity\ of\ biofuel\ [t] * lower\ heating\ value\ biofuel\left[\frac{MJ}{kg}\right]}$$

The following formula shall be used to calculate e_{ccs} (in g CO_2e per MJ):

$$e_{ccs}\left[\frac{g\ CO_2e}{MJ}\right] = \frac{produced\ CO_2[kg] - energy\ consumed[MWh] * EF\left[\frac{kg\ CO_2e}{MWh}\right] - input\ materials\ [kg] * EF\left[\frac{kg\ CO_2e}{kg}\right]}{produced\ quantity\ of\ biofuel\ [t] * lower\ heating\ value\ biofuel\left[\frac{MJ}{kg}\right]}$$

For the calculation of e_{ccr} and e_{ccs} the following information needs to be provided and verified:

- Produced quantity of biofuel
- Quantity of biogenic CO_2 captured during the biofuel production process
- Quantity of energy consumed for the capturing and the processing of CO_2 (e.g. compression and liquefaction)
- Other input materials consumed in the process of CO_2 capture and processing
- GHG emission factor and its source for all inputs



ISCC International Sustainability & Carbon Certification

e_{ccr} can only be taken into account if it can be proven that the CO_2 replaces fossil-derived CO_2 used in commercial products and services. One option to proof a commercial use of the biogenic CO_2 is by showing that the CO_2 has been commercially marketed or used directly.

e_{ccs} can only be taken into account if there are valid evidences that CO_2 was effectively captured and safely stored. If the CO_2 is directly stored it should be verified whether the storage is in good condition, leakages are nonexistent and the existing storage guarantees that the leakage does not exceed the current state of technology. If the CO_2 is sold for storage, one option to proof storage is to provide contracts and invoices of a professional recognized storage company.

2. Emission saving from soil carbon accumulation via improved agricultural management (e_{sca}):
Improved agricultural management refers to practices that lead to an increase in soil carbon. According to the Communication from the European Commission (2010/C160/02), this can include practices such as:

- Shifting to reduced or zero-tillage
- Improved crop rotations and/or cover crops, including crop residue management
- Improved fertilizer or manure management
- Use of soil improver (e.g. compost)

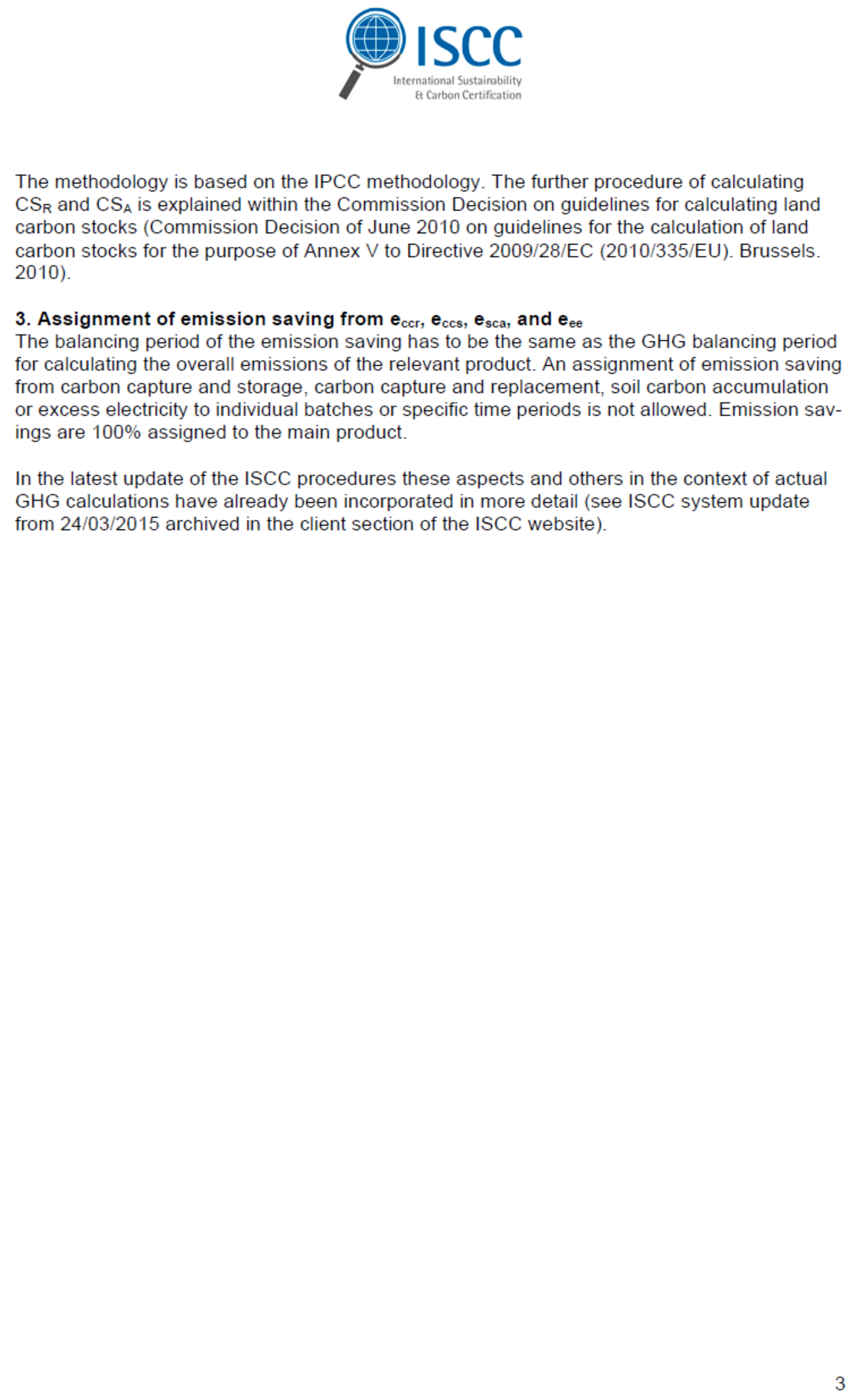
Emission savings from such improvements can be taken into account if evidence is provided that the above-mentioned practices have been adopted after January 2008. Furthermore, it must be verified that they are implemented in best practice so that an increase in soil carbon can be expected over the period in which the raw materials concerned were cultivated. Measurement of soil carbon could also serve as additional evidence.

For calculating e_{sca}, the formula as indicated in point 7, Annex V of the RED and as further specified in Annex II of the Communication from the Commission (2010/C160/02) shall be used:

$$e_{sca}\left[\frac{g\ CO_2e}{kg}\right] = \frac{(CS_R - CS_A)\left[\frac{g\ C}{ha * yr}\right] * 3.664\left[\frac{g\ CO_2}{g\ C}\right]}{period\ of\ cultivation\ of\ crops\ concerned\ [yrs]\ * P\left[\frac{kg}{ha}\right]}$$

Where:

e_{sca}	Annualized GHG emissions from carbon stock changes due to improved agricultural management
CS_R	Carbon stock per unit area associated with the reference land use (January 2008 or 20 years before the raw material was obtained, whichever was the later)
CS_A	Carbon stock per unit area associated with the actual land use (The estimated stock per unit area after 20 years or when the crop reaches maturity, whichever the earlier)
P	Productivity of the crop



The methodology is based on the IPCC methodology. The further procedure of calculating CS_R and CS_A is explained within the Commission Decision on guidelines for calculating land carbon stocks (Commission Decision of June 2010 on guidelines for the calculation of land carbon stocks for the purpose of Annex V to Directive 2009/28/EC (2010/335/EU). Brussels. 2010).

3. Assignment of emission saving from e_{ccr}, e_{ccs}, e_{sca}, and e_{ee}

The balancing period of the emission saving has to be the same as the GHG balancing period for calculating the overall emissions of the relevant product. An assignment of emission saving from carbon capture and storage, carbon capture and replacement, soil carbon accumulation or excess electricity to individual batches or specific time periods is not allowed. Emission savings are 100% assigned to the main product.

In the latest update of the ISCC procedures these aspects and others in the context of actual GHG calculations have already been incorporated in more detail (see ISCC system update from 24/03/2015 archived in the client section of the ISCC website).

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