Regional Differences in Life-Cycle Greenhouse Gas and Criteria Air Pollutant Emissions of Light-Duty Vehicles in the United States

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ABSTRACT

To facilitate the efforts to identify greenhouse gas (GHG) and criteria air pollutants (CAP, representing CO, VOC, NO_x, SO_x, PM_{10} and $PM_{2.5}$) emission-reduction opportunities that may be specific to particular regions, this paper intends to estimate regional differences in life-cycle GHG and CAP emissions from light-duty vehicles in the US, using the GREET (the Greenhouse gases, Regulated Emissions, and Energy use in Transportation) Model, a life-cycle analysis model that has been developed at Argonne National Laboratory to quantify life-cycle GHG and CAP emissions from both conventional and advanced vehicle/fuel systems. The GHG and CAP emission burdens of upstream crude oil recovery, transportation, refining and distribution activities associated with the production of gasoline and diesel from both domestic and foreign crude oil sources for the US transportation sector are explored in each of the Petroleum Administration for Defense Districts (PADD) regions. Besides, GHG and CAP emission factors of light-duty vehicle operation on the county level are calculated by using EPA's MOVES model. Results show that the life-cycle GHG and CAP emissions induced by fuel use by both gasoline and diesel light-duty vehicles differ to a varying extent among the PADD regions, due to regional differences in GHG and CAP emissions associated with various life-cycle stages, in PADD-specific crude oil source profiles, and in the vehicle operation emission factors.

INTRODUCTION

An accurate assessment of current and future advanced vehicle/fuel system options of their energy-saving and emission reduction potentials requires a complete vehicle fuel-cycle analysis, known as a well-to-wheels (WTW) analysis. For this purpose, a WTW analysis of conventional vehicle/fuel systems serves as the comparison basis for accurate evaluation of current and future vehicle/fuel systems within a methodology-and-data consistent framework, and therefore requires scrutinous examination with latest high quality data to reflect the impact of technology advances.

Life-cycle analysis (LCA) has become a widely used tool in recent years to estimate environmental effects of the entire life-cycle of transportation vehicle/fuel systems. While the accuracy and level of aggregation of data are essential for credible LCA, regional LCA is recognized as an important step towards improving the accuracy and precision of LCA which typically uses national aggregate data, thereby increasing its fidelity for comparative assessments. In addition, many decisions by regional policy makers would be better informed by regionalizing data and analysis to identify such damages as photochemical ozone pollution, acidification or toxicological impacts on humans and ecosystems, which are in close relationship with greenhouse gas (GHG) and air pollutant emissions (Cicas et al., 2007).

This paper attempts to examine the regional differences in life-cycle GHG and criteria air pollutant (CAP, including CO, VOC, NO_x, SO_x, PM_{10} and $PM_{2.5}$) emissions induced by fuel use by conventional gasoline and diesel light-duty vehicles (LDVs) in the United States, with a focus on the conventional gasoline and diesel LDVs, which are the dominant vehicle/fuel systems in the current US market. The goal of this work is to improve our understanding of the regional WTW GHG and CAP emissions of conventional LDVs fueled by petroleum-based transportation fuels among the Petroleum Administration for Defense Districts (PADD) regions, which include the East Coast Region (PADD1), Midwest Region (PADD2), Gulf Coast Region (PADD3), Rocky Mountain Region (PADD4), and the West Coast Region (PADD5) (EIA, 2012a), and to facilitate the recognition of the region-specific opportunities that are brought by introduction of various alternative vehicle/fuel systems to mitigate GHG and CAP emissions from LDVs.

METHODS and DATA

Regional Life-Cycle Analysis Approach

The regional LCA of conventional LDVs includes many well-to-pump (WTP) activities related to production and transportation of feedstocks and fuels, and the energy use and emissions associated with vehicle operations, or pump-to-wheels (PTW) activities. Figure 1 depicts the life-cycle analysis boundary and data flow of this study, which include crude oil extraction both at home and abroad, crude oil transportation from foreign port to domestic port and from domestic port to domestic refineries, domestic refinery of crude oil into finished petroleum products, transportation and distribution of refined products to refueling stations, and fuel combustion and evaporation due to the operations of conventional gasoline and diesel LDVs.

While the U.S. imported a fairly large portion of crude oil, which accounted for about 64% of the total crude oil that was refined into finished products in 2010 (EIA, 2012b), about 96% and 95% of the finished petroleum products of motor gasoline and diesel fuel consumed in the United States are produced domestically (EIA, 2011). Therefore, the petroleum-based fuel cycle analysis in this study considers only the crude oil recovery in both foreign countries and domestic states and does not consider the supply chain of imported petroleum products from foreign countries.

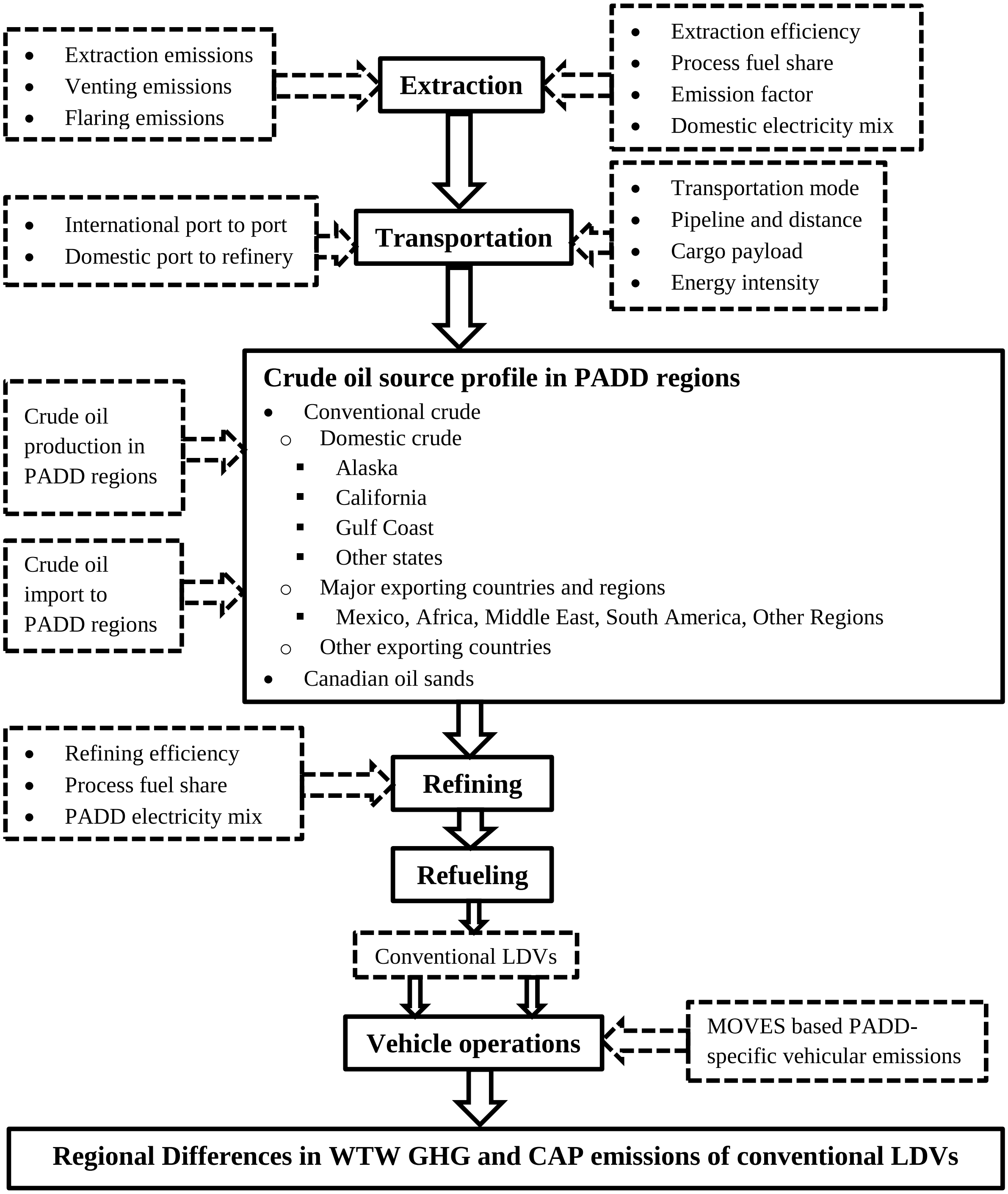


Figure 1. Life-cycle boundary and data flow of life-cycle stages of conventional gasoline and diesel production from both domestic and foreign crude oil

The WTW GHG and CAP emissions of US LDVs are calculated by using a fuel-cycle model developed by Argonne National Laboratory – the Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET) model (Wang, 1999a, b). In GREET, the CH_4, N_2O and

CAP emissions from WTP activities of each fuel production pathway are calculated based on the energy efficiency of each production activity, the use of various process fuels, and the emission factors for combusting process fuels by different combustion technologies, as depicted in Figure 2. For CO_2 emissions, GREET takes a carbon-balance approach by subtracting the carbon contained in combustion emissions of VOC, CO, and CH_4 from the carbon contained in the fuel burned (Wang, 1999a).

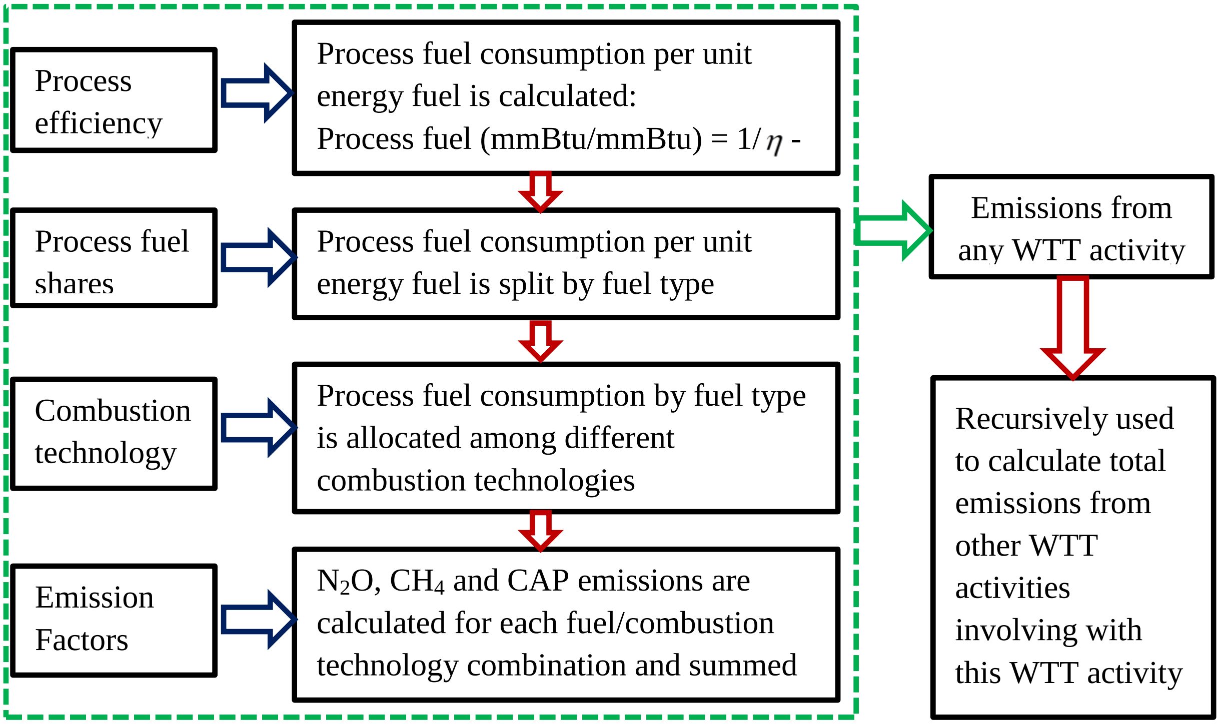


Figure 2. GREET methodology for WTP emission calculation.

The PTW emissions, which come from engine start, tailpipe running exhaust, fuel evaporation, refueling loss, and tire wear and brake wear, are modeled by using MOVES (version 2010a), EPA's mobile source emission factor model (EPA, 2011). The MOVES generated GHG (CO_2 excluded) and CAP emission factors are fed into GREET for PTW and WTW simulations.

This study uses the most current 2007 Intergovernmental Panel on Climate Change (IPCC) Global Warming Potential (GWP) values based on the 100-year time-frame, which are 1, 25, and 298 for CO_2, CH_4, and N_2O, respectively (IPCC, 2007), to estimate the CO_2 equivalent (CO_2e) amount of GHG emissions associated with various life-cycle stages.

Methods and Data for Each Life-Cycle Stage

Recovery of Crude Oil

The crude oil recovery stage of the petroleum fuel cycle includes oil extraction, oil gathering through gathering pipes, crude treatment in production fields, and crude storage in production fields. Crude, residual oil, and/or natural gas are burned, and electricity is consumed to provide energy for these processes, depending on the crude oil recovery methods used. While crude oil in seven states was 100% domestic production and crude oil in another five states was 100% imported, another 28 states simultaneously produced domestic crude oil and imported from other countries or regions (EIA, 2012b, 2012c). Therefore, we estimate the GHG and CAP emissions associated with the crude oil recovery in both foreign countries and domestic states in our PADD-level WTW analysis, which begins with the identification of the PADD-specific crude oil source profile, which presents the crude oil shares of both domestic production and import from various foreign countries and regions. We develop the PADD-specific crude oil source profile based on EIA' Company Level Imports data (EIA, 2012c), as well as EIA's domestic crude oil production data (EIA, 2012b) for 2010.

According to the geographic locations and country-specific data availability, the 42 foreign exporting countries are classified into six groups: 1) Canada and 2) Mexico, which are the two leading exporting countries to the U.S.; 3) South America including Venezuela, Colombia, Brazil, Ecuador, Argentina, Peru and Boliva; 4) Middle East including Saudi Arabia, Iraq, Kuwait, Oman, Egypt, and United Arab Emirates; 5) Africa including Nigeria, Angola, Gabon, Equatorial Guinea, Congo, Cameroon, Libya, Chad, Cote D'Ivoire, and Mauritania; and 6) Other Regions including Russia, Azerbaijan, Trinidad & Tobago, Indonesia, Norway, Kazakhstan, Thailand, Vietnam, Guatemala, Australia, China, Malaysia, Netherlands, and Belize, which account for only 10.08% of the total crude oil importation by the U.S.

Crude oil recovery technology varies from state to state and from country to country, and the resultant energy efficiency and process fuel shares associated with each recovery technology, which determine the GHG and CAP emissions during the oil recovery process, differ among states and countries. Table 1 summarizes the literature based state-specific and country-specific energy efficiency and process fuel shares per barrel of crude oil recovered from representative oil fields in both domestic states and the major exporting countries (TIAX and MathPro, 2009).

Table 1. Efficiencies and process fuel shares for crude oil recovery by state and region (TIAX and MathPro, 2009)

State or region	Representative Crude oil	Efficiency	Electricity credit (Btu/mmBtu)	Process fuel shares		
				Produced gas	Pipeline NG	Grid electricity
California	California heavy crude	63.40%	195,089	0%	100%	0%
Alaska	Alaska medium crude	98.80%	0	100%	0%	0%
US Gulf Coast	Gulf Coast medium crude	99.70%	0	100%	0%	0%
Middle East	Saudi Arabian medium crude	99.90%	0	94%	0%	6%
	Iraq medium crude	99.80%	0	94%	0%	6%
Mexico	Mexico heavy crude	98.40%	0	4%	95%	1%
South	Venezuela heavy crude	87.90%	0	65%	35%	0%

America						
Africa	Nigeria light crude	99.80%	0	90%	0%	10%
Canada	Canada heavy crude	98.20%	0	100%	0%	0%

For the Other Regions, where a representative crude oil recovery profile is not available to us, the GHG and CAP emission profiles associated with crude oil recovery there are estimated by establishing a simplified relationship between crude oil quality and the associated recovery efficiency and process fuel shares, based on the crude oil quality, energy efficiencies and process fuel shares in countries and states listed in Table 1, which indicates that the efficiency and process fuel shares for crude oil recovery is related to the crude oil quality. Table 2 summarizes the crude oil quality dependent energy efficiencies and process fuel shares for crude oil recovery.

Table 2. Energy efficiencies and process fuel shares for recovering crude oil of different quality

Crude oil quality	Efficiency	Process fuel shares		
		Produced gas	Pipeline natural gas	Grid electricity
Light crude oil[1]	99.8%	90%	0%	10%
Medium crude oil[2]	99.5%	95%	0%	5%
Heavy crude oil[3]	95.0%	42.5%	57.5%	0%

[1] having an API gravity higher than 31.1 ° API

[2] having an API gravity between 22.3 °API and 31.1 °API (870 to 920 kg/m^3)

[3] having an API gravity below 22.3 °API (920 to 1000 kg/m^3)

To apply the crude oil quality dependent energy efficiencies and process fuel shares in Table 2 to each country of the Other Regions based on their identified crude oil quality, we further identify the crude oil quality from each specific countries in the Other Regions, as shown in Table 3, by identifying the crude oil's American Petroleum Institute (API) gravity based on the heat content of crude oil by country (EIA, 2012d) and the relationship between heat content and crude oil API (Schmidt, 1985). A composite energy efficiency and process fuel share for the Other Regions, as shown in Table 4, is finally developed based on the relative shares of crude oil of different qualities and their efficiencies and process fuel shares.

Table 3. API based identification of crude oil quality from specific countries in the Other Regions

Country	Crude oil quality	Country	Crude oil quality	Country	Crude oil quality
Russia	Medium crude	Guatemala	Medium crude	Thailand	Heavy crude
Azerbaijan	Medium crude	Vietnam	Medium crude	Kazakhstan	Medium crude
Trinidad And Tobago	Medium crude	Australia	Light crude	Netherlands	Heavy crude
Norway	Light crude	China	Medium crude	Belize	Light crude
Indonesia	Light crude	Malaysia	Light crude		

Table 4. A composite energy efficiency and process fuel share for crude oil recovery in the Other Regions

	Efficiency	Process fuel shares		
		Produced gas	Pipeline natural gas	Grid electricity
Other Regions	99.4%	92.8%	1.7%	5.5%

For the hydrocarbon deposits called bitumen, which are also referred to as oil sands in Canada, they must be mined, separated from the sand and other minerals and either blended with a light oil or upgraded to create a synthetic crude so that it can be transported and processed by existing refineries. Two different recovery techniques are utilized to recover Canadian oil sands: surface mining and in-situ thermal recovery. In both cases we have utilized GREET default energy efficiency and process fuel shares for bitumen extraction and bitumen upgrading, to quantify the associated GHG and CAP emissions. Particularly, the Canadian electricity generation mix is applied to reflect the local emission characteristics of generating electricity used by oil sand recovery.

Another emission source associated with crude oil recovery is flaring and venting. Gas flaring varies dramatically from near zero in Saudi Arabia to as high as 20% of the crude energy content in Nigeria (Jacobs, 2010). Therefore, we collect the country-specific GHG and CAP emissions associated with flaring and venting during crude oil recovery based on the venting and flaring data from the World Bank, US EPA, US EIA, CARB, and local agencies.

The PADD-specific crude oil source profile and these best available state- and region-specific crude oil recovery data ensure an accurate estimation of the emission burdens associated with the crude oil recovery on the PADD level, and are thus important for the credible life-cycle GHG and CAP emission estimation of petroleum related products in the U.S.

Crude Oil Transportation to Refining States

The GHG and CAP emissions associated with crude oil transportation are calculated based on travel mode shares, distance traveled by mode, energy intensity (Btu/ton-mile) and fuel type by transport mode, and emission factors for each transport mode/fuel type combination. Three phases of crude oil transportation to U.S. refineries are considered: 1) Pipeline transportation within the exporting country. For all foreign crude oil sources for U.S. refineries, the crude oil is assumed to be transported 100 miles via pipeline to an ocean port; 2) Ocean tanker transportation from foreign ports to the US receiving ports. With information on the foreign crude oil exporting ports (EIR, 2006) and the largest receiving ports in each PADD region (EIA, 2012e), the international port-to-port transportation distances for all crude oil imports in each PADD region are recognized by using the Portworld Distance Calculator (Petromedia, 2012), with transportation through the Panama Canal, Suez Canal, and Bosporus Strait disallowed. Canadian and Mexican exports received by US states are assumed to be via pipeline; and 3) Domestic crude oil transportation to refineries via a combination of pipeline, barge, rail, and truck. The default GREET parameters are used to characterize the intra-PADD transportation of crude oil.

Refining of crude oil into finished fuels

GHG and CAP emissions associated with refining come from the acquisition, production and combustion of process fuels. Crude oil properties like crude distillation curve, sulfur content, and chemical composition influence the amount of process fuel consumption by the refineries to produce finished fuels. Because crude oil properties vary by crude oil sources, regional differences in energy efficiencies and process fuel use by refineries, and eventually in GHG and CAP emissions from crude oil refining are expected, due to regional differences in the refinery crude mixes, product slates, and refinery configuration. We use the recently estimated petroleum refinery energy efficiencies and process fuel shares by PADD (Ignasi et al., 2011), as shown in Table 5, to feed into GREET, which calculates the emission burdens associated with the acquisition, production and combustion of all types of process fuels for petroleum refining in each PADD region.

Table 5. Petroleum refinery energy efficiencies and process fuel shares by PADD region

		PADD I	PADD II	PADD III	PADD IV	PADD V
Efficiencies		95.0%	91.4%	91.0%	89.8%	91.2%
Process fuel shares	Residual oil	46.0%	39.2%	21.6%	51.9%	24.9%
	Natural gas	26.1%	26.2%	37.1%	22.9%	37.4%
	LPG	0.1%	10.5%	10.1%	3.9%	8.0%
	Electricity	9.0%	5.8%	5.2%	5.4%	3.5%
	H_2	18.3%	18.4%	26.1%	16.0%	26.2%
	Coal	0.5%	0.0%	0.0%	0.0%	0.0%

Transportation and distribution of finished petroleum products

The default GREET parameters are used to characterize the intra-PADD transportation and distribution of finished petroleum products.

Vehicle operation emissions

Both tailpipe emissions due to fuel combustion, as well as emissions from fuel evaporation and brake and tire wear are estimated on the county level by MOVES, to account for the effect of local meteorology, fuel specifications and I/M schemes on the emission characteristics of gasoline and diesel LDVs, by using the US average driving speed distribution, vehicle miles traveled distribution, LDV age distribution, road type distribution and ramp fraction, as well as the county-specific meteorology, fuel and inspection and maintenance (I/M) scheme data. The county-level emission factors are then aggregated to the PADD level based on the vehicle registration number in the state to which the county belongs.

Electricity Generation Mixes

Electricity is used as a process fuel in crude oil recovery at oil field, in crude oil transportation, in crude oil refining and in distribution of finished petroleum products to refueling stations. Electricity consumption associated with these activities comes from various sources, and should have distinct GHG and CAP emission burdens due to differences in electricity generation mixes, electricity generation efficiencies, generation technology shares, and emission factors for various types of generation technologies by fuel type. Therefore, to account for the emissions associated with electricity consumption both at the foreign oil field, during foreign and domestic transportation, and in the domestic refineries for the same pathway, we have recently developed US state-specific electricity generation mixes, efficiencies, generation technology shares, and emission factors by fuel type and generation technology for the power sector using EPA's eGRID database, WebFIRE and AP-42 emission factor databases, EIA's fuel consumption and fuel quality databases, and open literature (Cai et al., 2012), and we use those detailed state-level parameterizations of the power sector to build a PADD-level composite parameterization for PADD-specific WTW analysis. For foreign regions that export crude oil to the U.S., the electricity generation mixes, efficiencies, generation technology shares, as well as the transportation loss factors are collected based on International Energy Agency's statistical database for electricity and heat (IEA, 2012)

RESULTS AND DISCUSSION

Regional Differences in Life-Cycle GHG and CAP Emissions of Conventional Gasoline and Diesel LDVs

To explore the sources of and regional variability in WTW GHG and CAP emissions from LDVs, which would be useful for designing regional GHG and CAP mitigation policy, we depict the life-cycle GHG and CAP emissions induced by fuel use by conventional gasoline and diesel LDVs among the PADD regions, as shown by Figure 4.

The life-cycle GHG emissions of both gasoline and diesel LDVs show a slight variation by 7.5% among the PADD regions, with the highest in PADD 5 and the lowest in PADD 1, as shown by Figure 4 (a). This regional difference is attributable to the regional GHG emissions from each life-cycle sources, as the GHG emissions associated with crude oil recovery, crude oil transportation, crude oil refining, gasoline distribution and vehicle operations vary by 38%, 48%, 45%, 16% and 3%, respectively. The life-cycle GHG emissions from diesel LDVs have similar regional variability among the PADD regions, which is mainly due to identical WTP emissions and a moderately different tailpipe GHG emissions of diesel engines from the gasoline ones, and the GHG emission reduction potentials of diesel LDVs over gasoline ones vary slightly from 10.5% in PADD 5 to 11.7% in PADD 1.

A notable regional variation in the life-cycle VOC emissions of both gasoline LDVs and diesel LDVs is found, as shown by Figure 4 (b), which mainly results from the significant regional differences in VOC emissions from crude oil recovery. Compared to the WTW VOC emissions of gasoline LDVs, the relative changes in WTW VOC emissions of diesel LDVs varied by about 8.6% in PADD 1 and by about 27.3% in PADD 4, which indicates that similar or even more significant regional differences in emission reduction potentials by other vehicle/fuel systems like plug-in hybrid electric vehicles and battery electric vehicles are possible, and identification of such regional differences is invaluable to policy-makers to initiate the development plan for advanced vehicle technology and/or alternative fuel systems to achieve region-unique emission reduction goals by local or regional agencies. The higher tailpipe VOC emissions from diesel LDVs than gasoline ones is because Tier 1 emission standard for diesel LDVs was still in effect for vehicles in operation in 2005, which has higher VOC emission limit for diesel LDVs than gasoline LDVs (EPA, 2006, 2009), and the vehicle model year 2005 is modeled by MOVES and the results are used by GREET for life-cycle modeling for calendar year 2010, as GREET assumes a five-year lag of vehicle technology maturity during its simulation.

The life-cycle CO emissions for both gasoline and diesel LDVs has slight regional differences, as shown by Figure 4 (c), because the vehicle tailpipe CO emissions, which are the dominant life-cycle source, are close among the PADD regions, and other life-cycle source emissions are trivial.

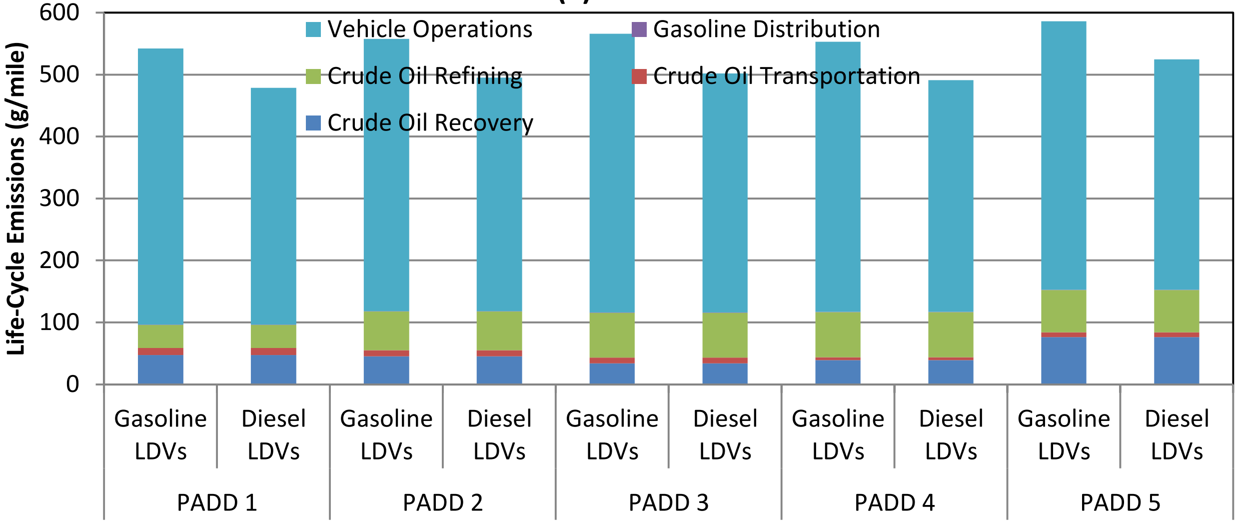
Figure 4 (d) shows a significant regional variation in life-cycle NO_x emissions for gasoline LDVs, with the lowest observed in PADD 4 at 0.234 g/mile and the highest in PADD 5 at 0.426 g/mile, mostly due to very distinct emissions in each life-cycle stage among the regions. The diesel LDVs, however, have a much smaller regional difference, because the tailpipe NO_x emissions, which are the dominant life-cycle source, are similar among the PADD regions. Nevertheless, the extra NO_x emission burdens added by diesel LDVs to gasoline ones differ significantly from 332% in PADD 5 to 670% in PADD 4.

The life-cycle PM_{10} emissions for gasoline and diesel LDVs are highest in PADD 4 and lowest in PADD 5, which is mainly contributable to the emission difference associated with crude oil refining, as shown in Figure 4 (e). The life-cycle PM_{10} emissions for gasoline LDVs are close to those from diesel ones within the same region, with the identical WTP emissions and similar emission burdens due to vehicle operations.

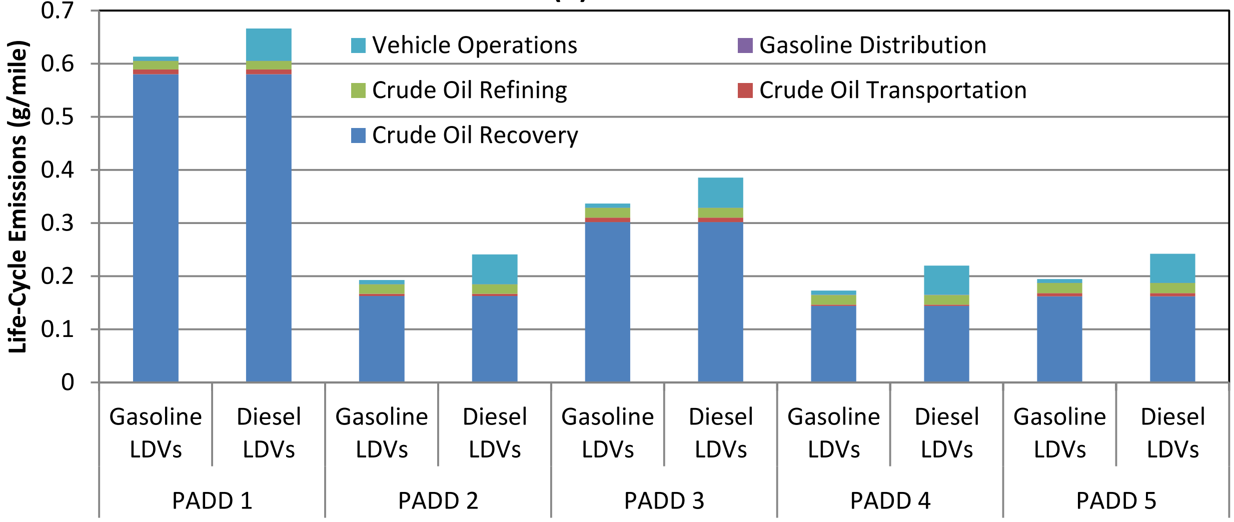
Differing significantly in emissions associated with various WTP activities among the regions, the WTW $PM_{2.5}$ emissions, however, show a slighter regional variation than intra-regional variation in emissions from various life-cycle stages, as shown by Figure 4 (f).

With significant differences in SO_x emissions from crude oil transportation among the regions, the life-cycle SO_x emissions also vary dramatically among the regions, with the highest observed in PADD 1 at 0.204 g/mile over twice as much as that in PADD 4, as shown by Figure 4 (g).

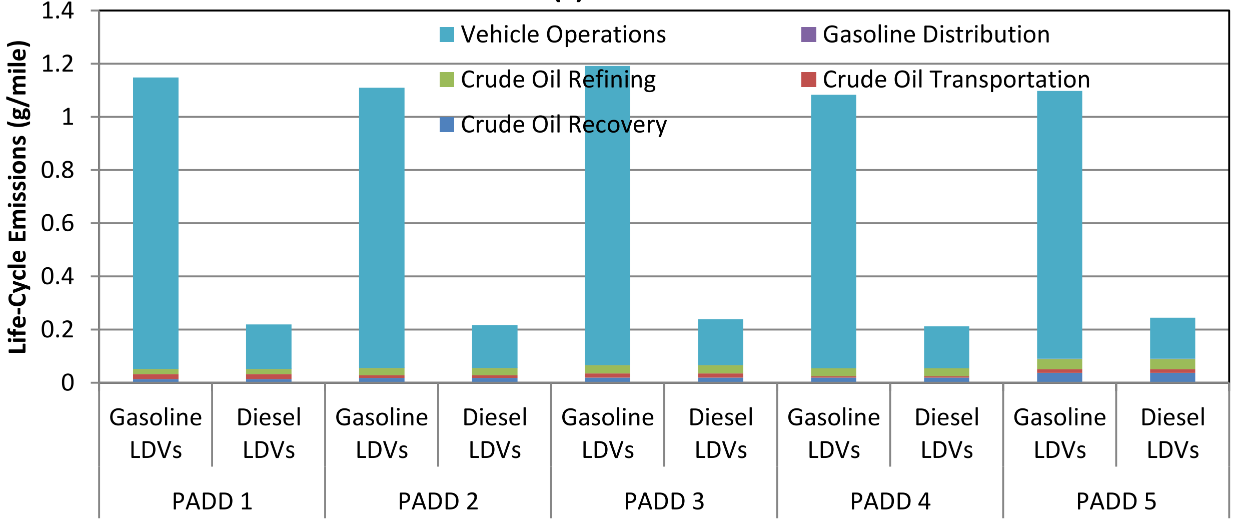
(a) GHG

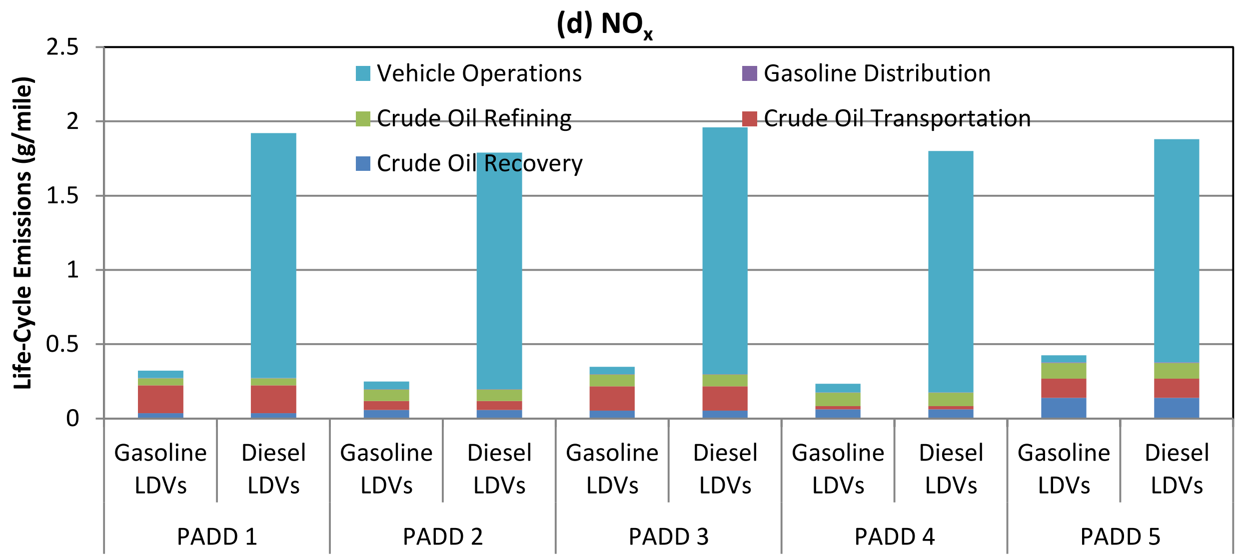


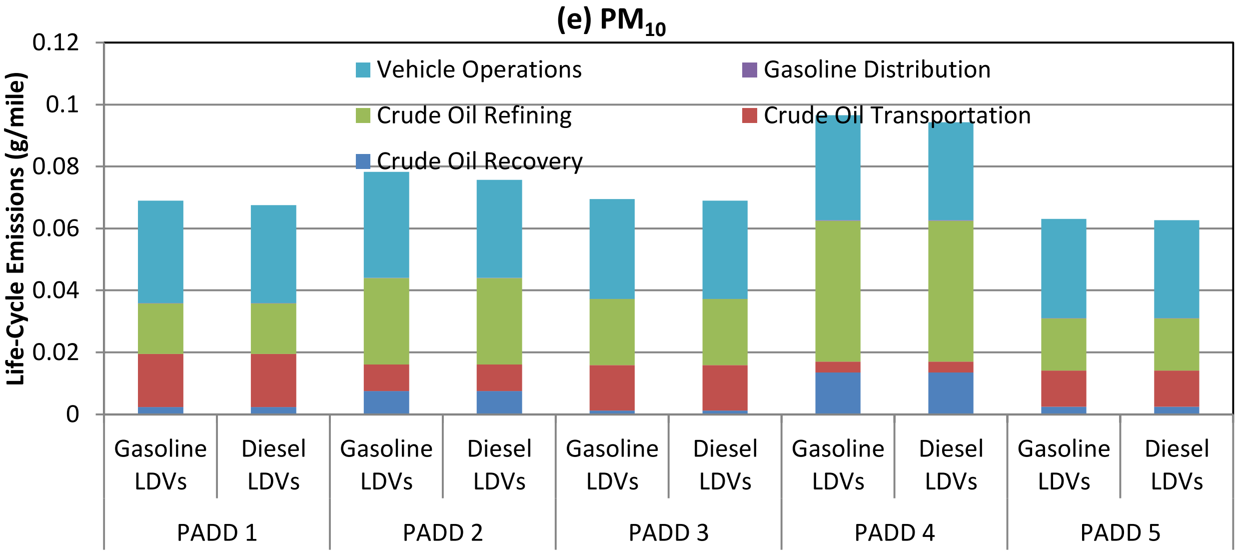
(b) VOC

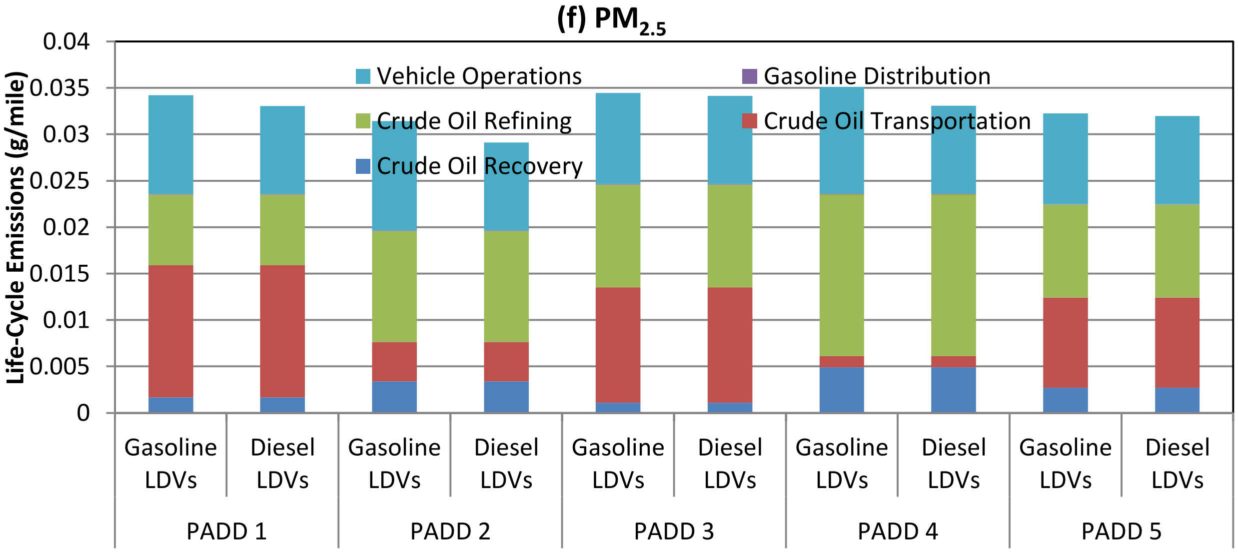


(c) CO




(d) NO_x


(e) PM_{10}


(f) $PM_{2.5}$

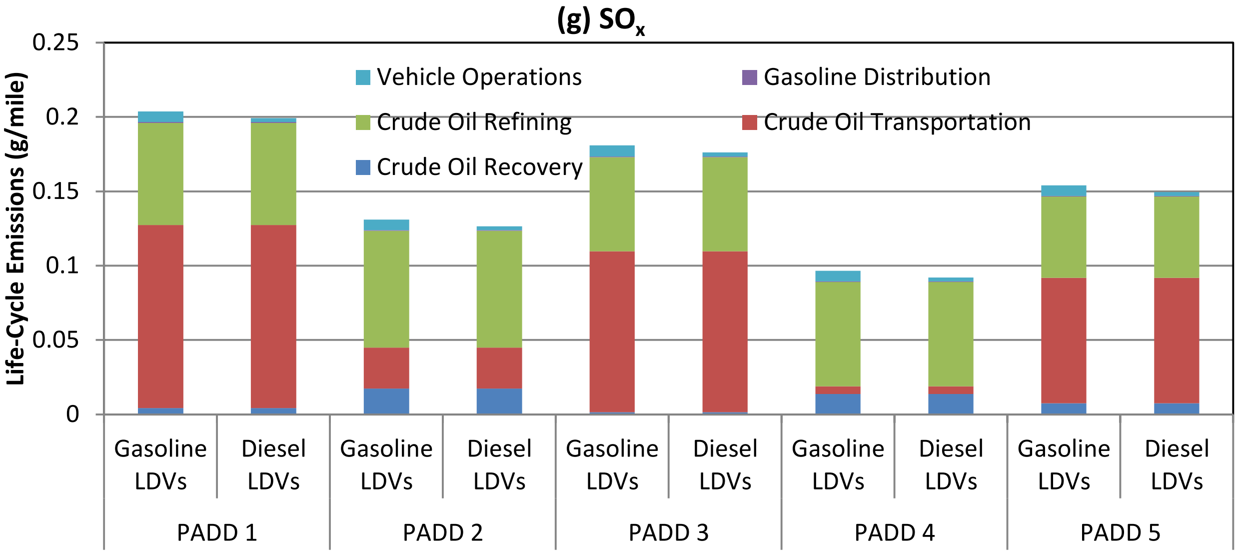


Figure 4. Regional life-cycle emissions of (a) GHG; (b) VOC; (c) CO; (d) PM_{10}; (e) $PM_{2.5}$; (f) NO_x; and (g) SO_x induced by fuel use by conventional gasoline and diesel LDVs among PADD regions

CONCLUSION

Regional life-cycle analysis of GHG and CAP emissions of the transportation sector is of interest to decision-makers owing to the recognition of local environmental impacts. Using company-level crude oil imports data and PADD-level crude oil production data from EIA, the PADD-specific crude oil source profile is developed, which serves as the basis for life-cycle analysis of GHG and CAP emissions of US conventional gasoline and diesel LDVs. The PADD-specific parameters like energy consumption by fuel type, efficiency, and the emission characteristics from local electric power sector for characterizing the life-cycle stages of crude oil recovery, transportation and refining, finished petroleum product distribution, and vehicle operations are thoroughly compiled through literature review, data analysis, and model simulations, and are fed into GREET to perform an up-to-date estimation of the emission characteristics for each of the life-cycle stages. This approach results in a state-of-the-art regional life-cycle analysis of GHG and CAP emissions of conventional gasoline and diesel LDVs in the U.S.

The life-cycle GHG and CAP emissions of both gasoline and diesel LDVs show regional differences of a varied magnitude, which depends on the combination of emissions variation for each life-cycle stage among the regions. Such improved understanding of the region-specific WTW GHG and CAP emissions from gasoline LDVs could serve as the baseline to facilitate the recognition of region-unique emission reduction potentials by advanced vehicle/fuel systems like plug-in hybrid electric vehicles and battery electric vehicles. Besides, the regional differences in WTW emissions between gasoline and diesel LDVs reveal that a life-cycle analysis of the emission reduction potentials by various advanced vehicle/fuel systems need to be performed on a region-specific basis, and the advanced vehicle/fuel systems with highest achievable emission reduction potentials should be encouraged in the regional differentiated policy packages that target on GHG and CAP emission reduction from the transportation sector.

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