Modeling Spatially Resolved US Carbon Dioxide Emissions from the Supply Chains of Gasoline and Diesel Consumption

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November 23, 2022

Abstract

Transportation fuels flow through a complex supply chain from the point of crude oil extraction to the point of combustion. We present a model that tracks the movement of gasoline and diesel across the petroleum infrastructure network consisting of pipeline, tankers, trucks, trains, refineries, and blenders. While direct CO2 emissions, from combustion, outweigh all supply chain emissions from processing and fuel movement, the indirect CO2 emissions also contribute a not insignificant amount of emissions driven by demand of transportation fuels. We resolve county-scale supply chain (Scope 3) CO2 emissions using publicly accessible data to quantify fuel movement between different linkages and transportation modes across the country. For most of the US, the exact volume of fuel moved between counties, from different refineries, along different modes of transportation, is not explicitly known. Linear optimization is used to model these flows with supply and demand related constraints. This work presents the most complete view of spatially-resolved scope-3 style CO2 emissions from United States' road transportation fuels. It offers a chance to investigate spatial patterns of scope-3 emissions across the country, as well as spatial differences between scope-1 and scope-3. Understanding embodied CO2 emissions of commodity flows across the US has implications for national and local policy.

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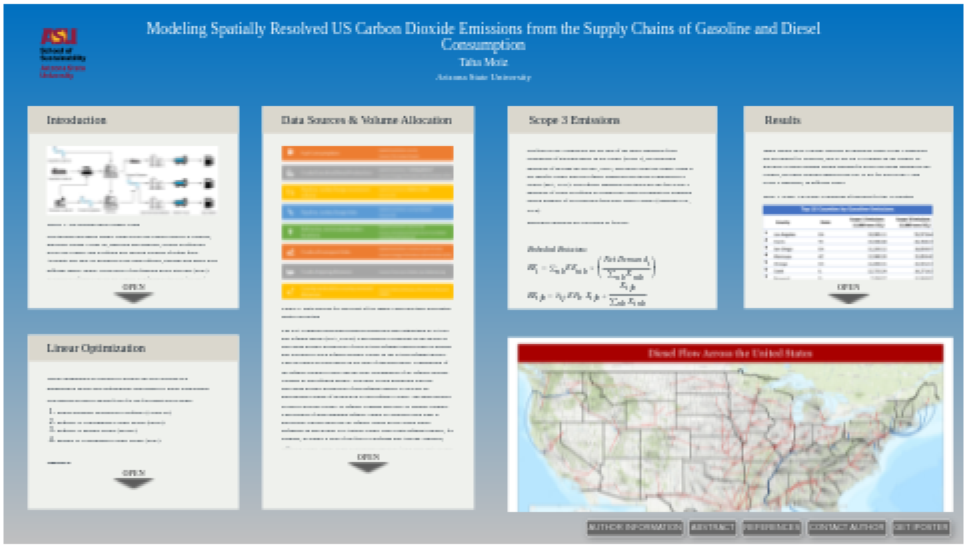

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INTRODUCTION

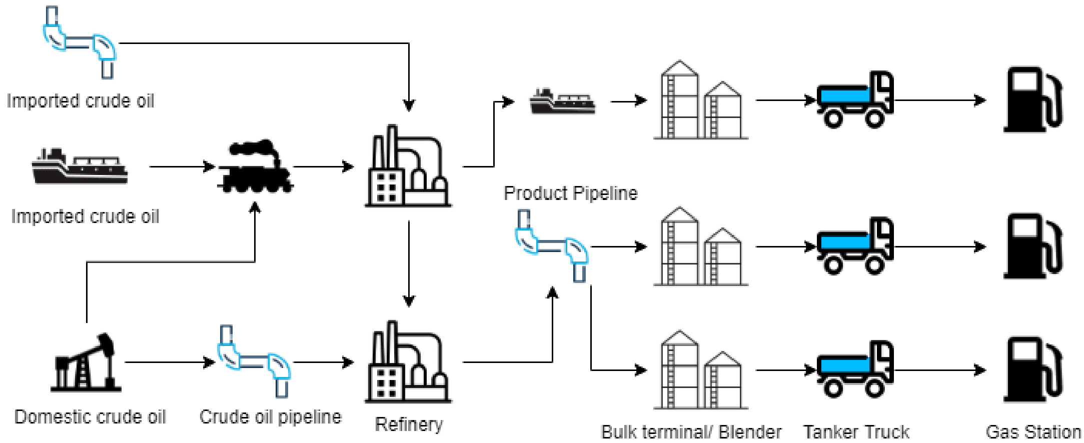


Figure 1. The gasoline/diesel supply chain

The gasoline and diesel supply chain across the United States is a complex, multi-tier system. Crude oil, imported and domestic, arrives at refineries across the country and is refined into varying volumes of liquid fuels. Although they may be produced at the same refinery, gasoline and diesel have different supply chains. While most of the finished motor gasoline (FMG) produced at refineries across the country is unfinished gasoline (MGBC), while diesel is produced close to its final form at the refineries. The unfinished gasoline is blended with ethanol and other blendstocks at petroleum terminals known as blenders, to produce finished motor gasoline (EIA, 2020b).

LINEAR OPTIMIZATION

Linear optimization is a method to achieve the best outcome in a mathematical model with requirements represented by linear relationships.

This method is used to model flows for the following sub-systems:

1. Import/Domestic production to Refinery (Crude oil)
2. Refinery to Consumption County Model (Diesel)
3. Refinery to Blender Model (MGBC)
4. Blender to Consumption County Model (FMG)

Objective:

Minimize the distance transported between demand and supply nodes times the cost of transporting between demand and supply nodes (Eq 1).

Constraints:

1. Conservation of mass - ensures that outflows from a county are less than equal to supply available at that county and inflows to a county are greater than equal to the demand at that county (Eq 2)
2. Constraint to enforce or restrict PADD to PADD flow for pipeline, waterborne, and truck movements (Eq 3) with 10% tolerance to account for data reporting and rounding errors.

Assumptions:

Each county with production first meets its own consumption demand, only excess volume is moved out.

The cost associated with each mode of transport has been assigned a fixed value across the country. Pipeline is the cheapest, followed by waterborne tankers, and tanker trucks are the most expensive mode. Water movements are 4 times as expensive as pipeline movements and truck movements are 6 times as expensive as pipeline movements. This forces the model to use truck movements as only a last-mile delivery resort. In the case of crude oil, railroads are also used, and is assigned the same cost as pipelines.

DATA SOURCES & VOLUME ALLOCATION

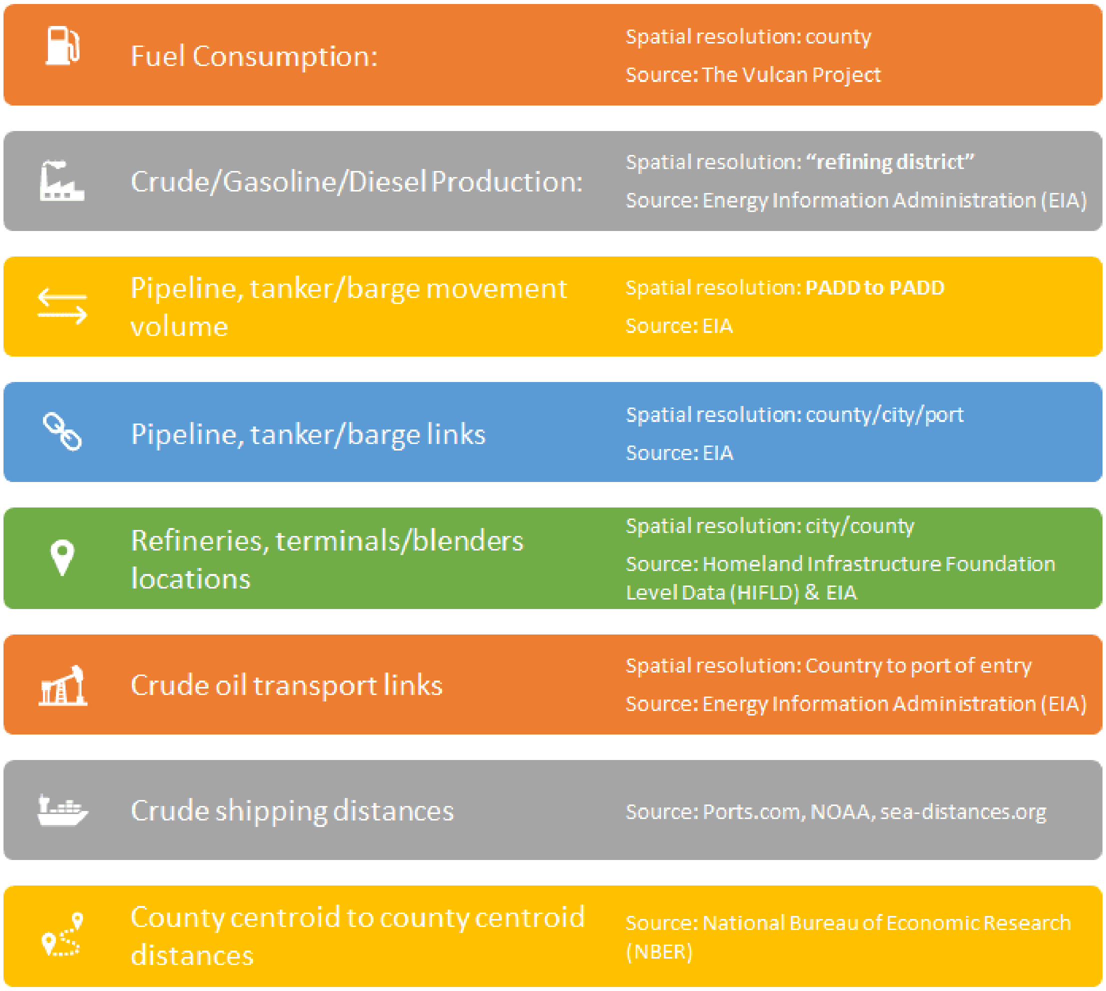


Figure 2. Data sources for each part of the supply chain and their associated spatial resolution

The EIA compiles petroleum products production data aggregated by PADD and refining district (EIA, 2020a). This presents a challenge in the model as petroleum product production of each PADD/refining district must be divided and allocated to each refinery/blender county in the PADD/refining district. This allocation is done based on the ratio of gasoline/diesel consumption of the refinery/blender county and the total consumption of all refinery/blender counties in that refining district. This ratio is then multiplied with the petroleum product production of that refining district to allocate an approximate volume of production to each refinery county. The same method is used to allocate MGBC to refinery counties and FMG to blender counties. This method of approximating refinery output is consistent with what is anecdotally known about the oil refinery output in the United States. Refineries in and around Los Angeles county with a high refining capacity, for example, do supply a bulk of the fuel to California and Arizona. Similarly, Jefferson county, Texas, home to Beaumont and Port Arthur have high volume of refining activity and thus the refining capacities at these locations is also high.

Example for production allocation:

$$LA\ County\ Production = \frac{LA\ County\ Consumption}{PADD\ 5\ Refinery\ Counties\ Total\ Consumption} \times PADD\ 5\ Total\ Production$$

SCOPE 3 EMISSIONS

The final scope 3 emissions are the sum of the direct emissions from combustion of gasoline/diesel in the county (scope 1), the embodied emissions of moving the MGBC, FMG, and diesel along the supply chain to the specific county and the refinery emissions per gallon combusted in a county (EPA, 2014). The refinery emissions per gallon are the full scope 3 emissions of crude oil refined at a particular county including the estimated carbon intensity of oil extraction from each source country (Masnadi et al., 2018).

Embodied emissions are calculated as follows:

$$Embodied\ Emissions$$

$$EE_i = \sum_{nk} EE_{nik} \times \left(\frac{Net\ Demand_i}{\sum_{nk} X_{nik}} \right)$$

$$EE_{ijk} = T_{ij}.\ EF_k.\ X_{ijk} + \frac{X_{ijk}}{\sum_{nk} X_{ink}} \times \left(\sum_{nk} EE_{nik} - EE_i \right) + PE_{ijk}$$

$$PE_{ijk} = CIB_i.\ X_{ijk}$$

$Where,$

$EE_{ijk} = Embodied\ emissions\ associated\ with\ volume\ link\ ijk$

$EE_i = Embodied\ emissions\ associated\ with\ volume\ consumed\ at\ county\ i$

$Net\ Demand_i = Consumption - production\ in\ county\ i$

$(Negative\ values\ are\ taken\ as\ zero)$

$PE_{ijk} = Embodied\ emissions\ of\ processing\ crude\ oil\ volume\ moved\ from\ county\ i\ to\ county\ j\ via\ transport\ mode\ k$

$CIB_i = Average\ carbon\ intensity\ of\ crude\ oil\ blend\ at\ origin\ county\ i$

$i = origin\ county$

$j = destination\ county$

$k = mode\ of\ transportation$

$n = other\ counties$

$X_{ijk} = volume\ of\ product\ in\ gallons\ moved\ from\ county\ i\ to\ county\ j\ via\ transport\ mode\ k$

$T_{ijk} = distance\ in\ miles\ between\ county\ i\ and\ county\ j$

$EF_k = emissions\ factor\ of\ transport\ mode\ k$

RESULTS

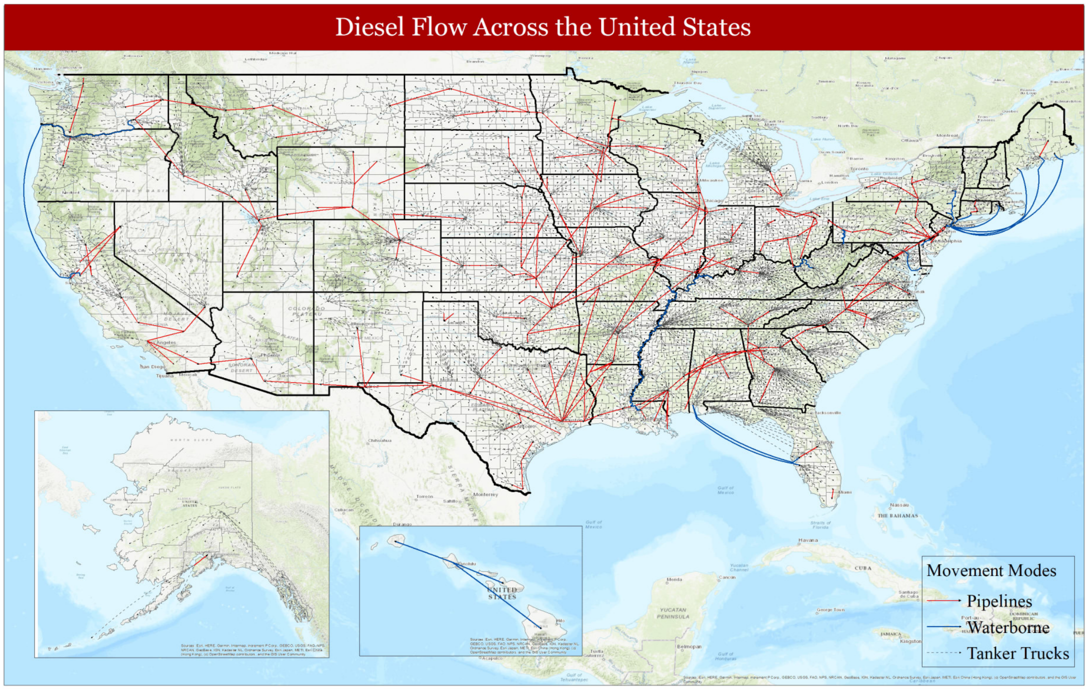
Initial results show a drastic increase in emissions when Scope 3 emissions are accounted for. However, due to the top 10 counties in the country by gasoline or diesel demand having demand far above the mean demand in the country, the same counties appear in the top 10 list for both scope 1 and scope 3 emissions, in different orders.

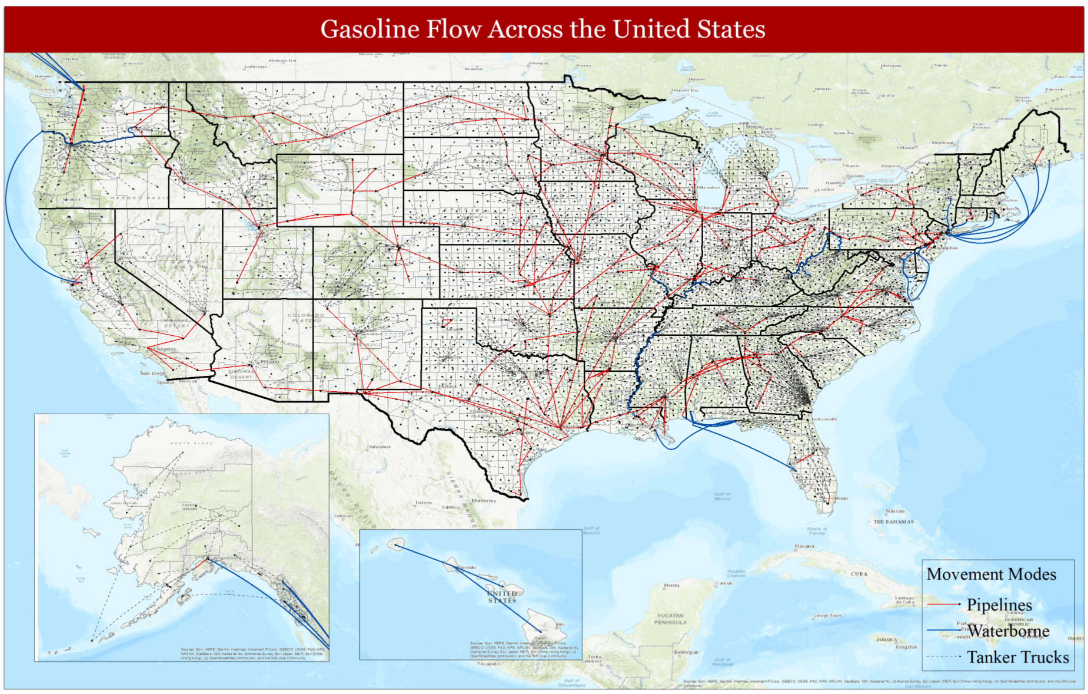
Table 1. Scope 1 & Scope 3 emissions of gasoline for top 10 counties

Top 10 Counties by Gasoline Emissions				
	County	**State**	**Scope 1 Emissions (1,000 tons CO_2)**	**Scope 3 Emissions (1,000 tons CO_2)**
1	Los Angeles	CA	33,985.11	55,973.64
2	Harris	TX	15,506.68	26,358.24
3	San Diego	CA	11,203.12	16,059.97
4	Maricopa	AZ	12,980.20	15,859.40
5	Orange	CA	11,060.31	15,501.53
6	Cook	IL	12,715.24	14,271.62
7	Broward	FL	7,358.57	12,968.85
8	San Bernardino	CA	8,306.62	11,965.76
9	Dallas	TX	9,245.18	10,552.90
10	Miami-Dade	FL	8,903.06	10,550.68
	Mean		*13,126.41*	*19,006.26*
	Standard Deviation		*7336.95*	*13049.50*
	National Mean		*381.88*	*513.27*
	National Standard Deviation		*1,072.68*	*1,587.20*

Table 2. Scope 1 & Scope 3 emissions of diesel for top 10 counties

Top 10 Counties by Diesel Emissions				
	County	**State**	**Scope 1 Emissions (1,000 tons CO_2)**	**Scope 3 Emissions (1,000 tons CO_2)**
1	Los Angeles	CA	5,886.74	6,917.52
2	Cook	IL	5,033.32	6,557.76
3	Maricopa	AZ	5,217.62	6,556.60
4	St. Louis	MO	3,442.79	5,475.41
5	Harris	TX	4,031.78	4,653.30
6	San Bernardino	CA	2,456.63	3,087.33
7	Kern	CA	2,591.46	3,003.37
8	King	WA	2,389.24	2,961.20
9	Dallas	TX	2,514.32	2,723.35
10	Riverside	CA	2,213.58	2,713.48
	Mean		*3,577.75*	*4,464.93*
	Standard Deviation		*1303.75*	*1679.95*
	National Mean		*127.01*	*147.40*
	National Standard Deviation		*278.18*	*341.40*


Diesel Flow Across the United States
Movement Modes
Pipelines
Waterborne
Tanker Trucks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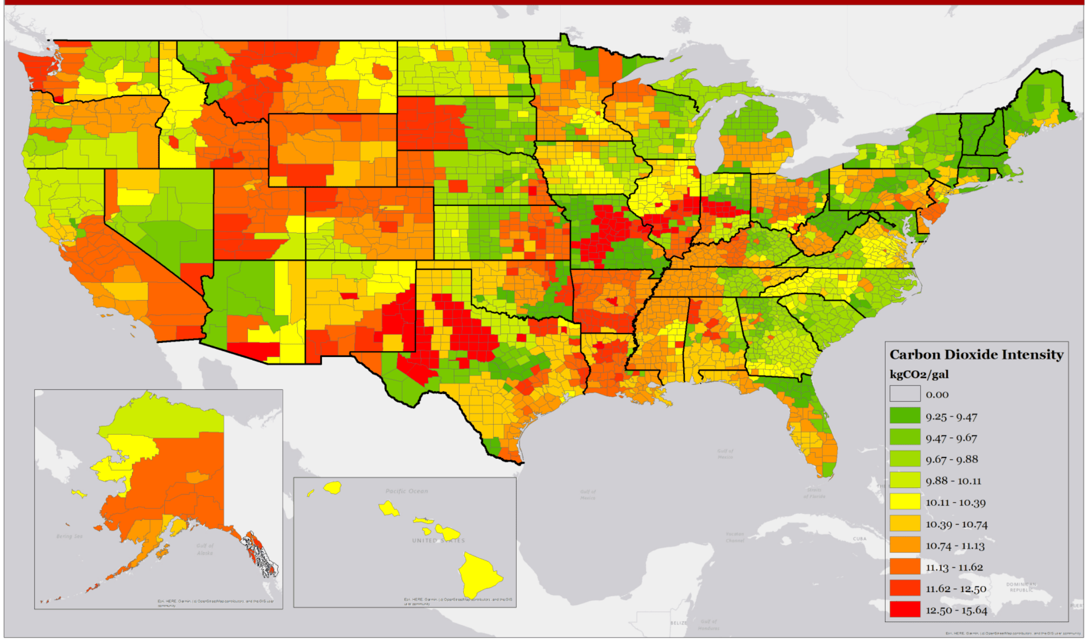
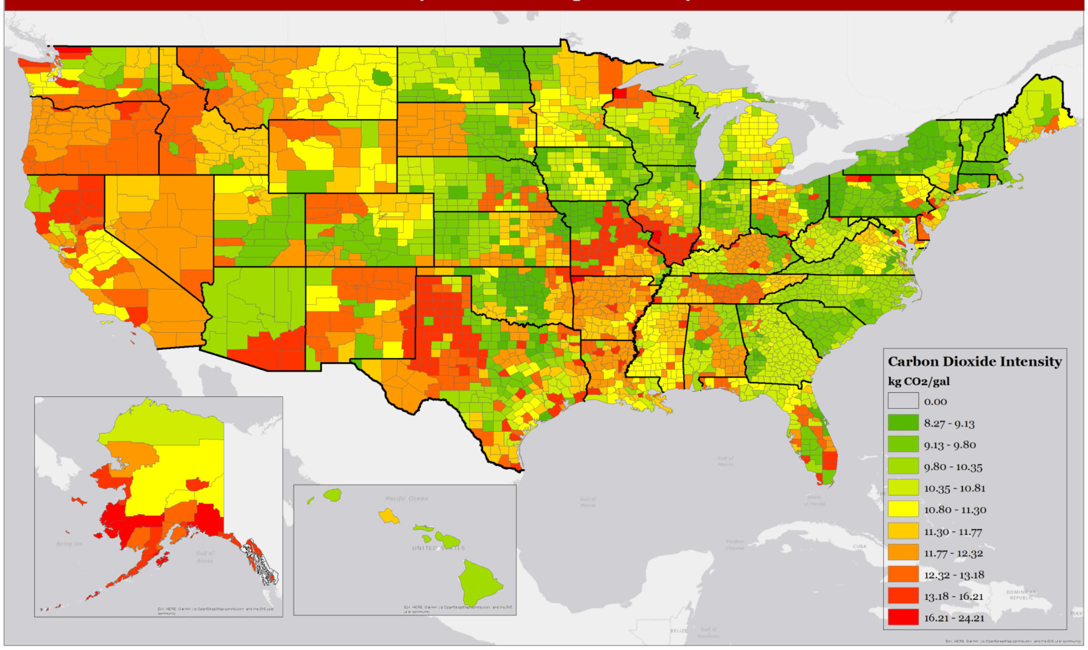
Carbon Dioxide Intensity of Diesel per County in the United States



Carbon Dioxide Intensity of Gasoline per County in the United States



AUTHOR INFORMATION

Taha Moiz is a doctoral student in the School of Sustainability at Arizona State University. He has a Bachelor's in Industrial and Manufacturing engineering from Pakistan and a Master's in Industrial and Systems engineering from Turkey. Taha has worked for a think tank focused on initiating smart and environmentally friendly solutions to public infrastructure challengesin Pakistan. He is interested in understanding how fossil fuels interact with the food, energy and water systems. Particularly in understanding how the broader fossil fuel system functions and where vulnerabilities and stresses exist. With this work Taha hopes to learn how climate change mitigation policies can be developed without disrupting the system.

ABSTRACT

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