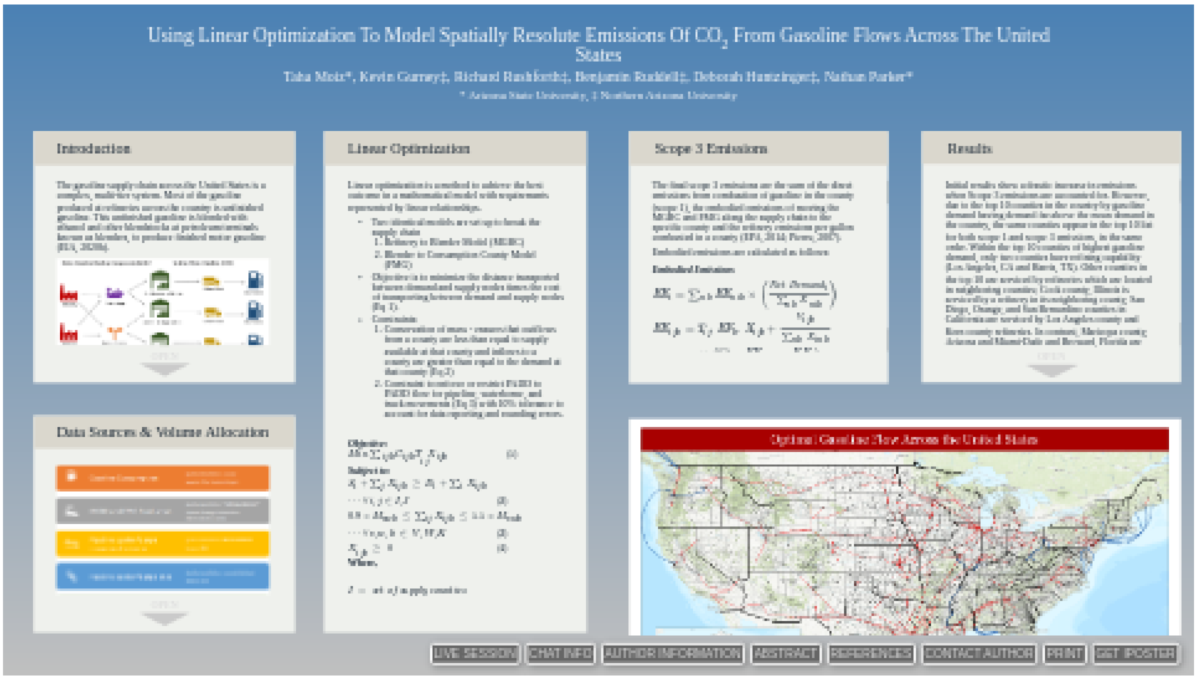
Using Linear Optimization To Model Spatially Resolute Emissions Of CO_2 From Gasoline Flows Across The United States



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INTRODUCTION

The gasoline supply chain across the United States is a complex, multi-tier system. Most of the gasoline produced at refineries across the country is unfinished gasoline. This unfinished gasoline is blended with ethanol and other blendstocks at petroleum terminals known as blenders, to produce finished motor gasoline (EIA, 2020b).

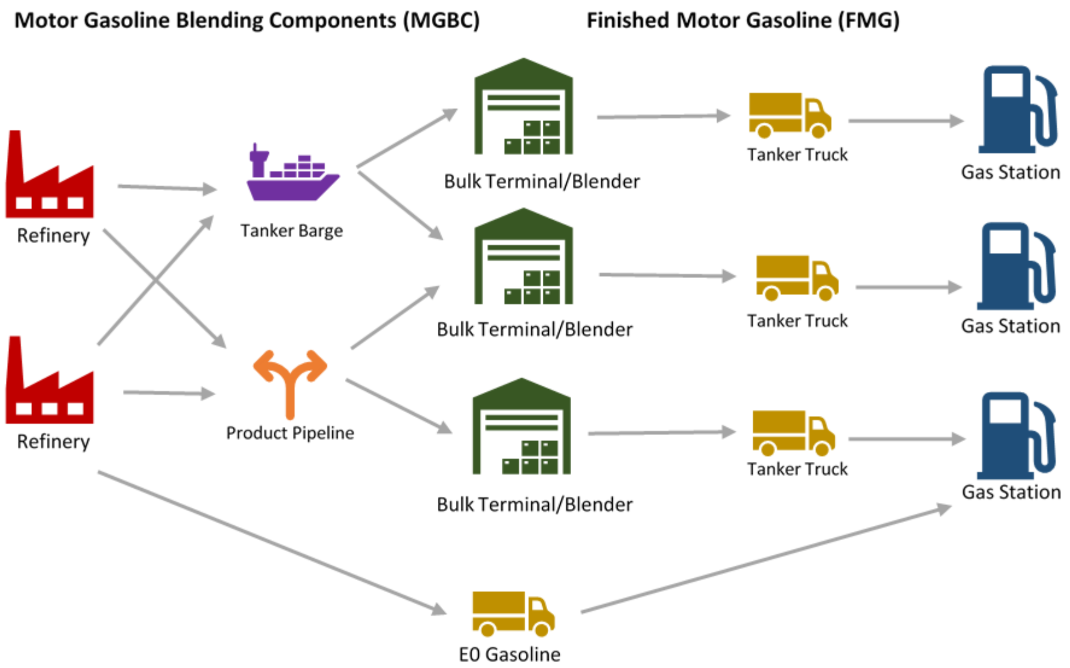


Figure 1. The two stage gasoline supply chain

The supply chain for gasoline can be simplified to a two-stage process as described in Figure 1. The first stage starts from the refinement of crude oil at the refinery to produced the unfinished gasoline. The Energy Information Administration (EIA) calls this Motor Gasoline Blending Components (MGBC). These blending components are moved from refineries to blenders, mostly via a network of pipelines across the country. A significant amount of MGBC also moves on barges via inland or coastal waterways. Some volume of MBGC also moves from refineries to blenders on tanker trucks. The blenders, through a separate stream, also receive fuel ethanol and other blending components that vary, among factors, by geographic location, season, and pollution control programs (EIA, 2020b).

The second stage of the supply chain starts from the blender and end at the point of consumption. MGBC is blended with fuel ethanol (and other additives/blendstocks) to make Finished Motor Gasoline (FMG). The ratio of ethanol to MGBC varies across the country based on factors such as season, and local regulations. The bulk of the MGBC is blended with ethanol and other blending components at the blenders while it is being filled into tanker trucks before delivery to retail fueling stations. Prior to blending, unblended gasoline is moved via pipelines or waterborne tankers/barges to other blenders. No ethanol blended gasoline is moved on the pipeline system or river/coastal waterways.

This work models the gasoline flow across the United States to estimate the scope 3 emissions of gasoline at a county-scale for the year 2012. The Energy Information Administration has annual time series data of MGBC and FMG production along with volumes of these products types moved by pipeline and waterborne tankers/barges at a “refining district” or Petroleum Administration for Defense (PAD) District spatial level (EIA, 2020a). The MGBC production volume serves as the upstream refinery output for the first stage of the supply chain and the FMG production volume serves as the blender output for the second stage of the supply chain. Downstream consumption of gasoline for the model is taken from the Vulcan Project Version 3.0 which quantifies fossil fuel carbon dioxide emissions at a 1 km x 1 km spatial resolution and time period from 2010-2015 (Gurney et al., 2020). The distribution of MGBC and FMG from refineries to blenders to counties of consumption across pipeline, waterborne barges, and tanker trucks is done using linear optimization for each county to county link. Finally, the output from the optimization model is converted to kg CO_2 to estimate the embodied emissions from gasoline for each county in the United States.

DATA SOURCES & VOLUME ALLOCATION

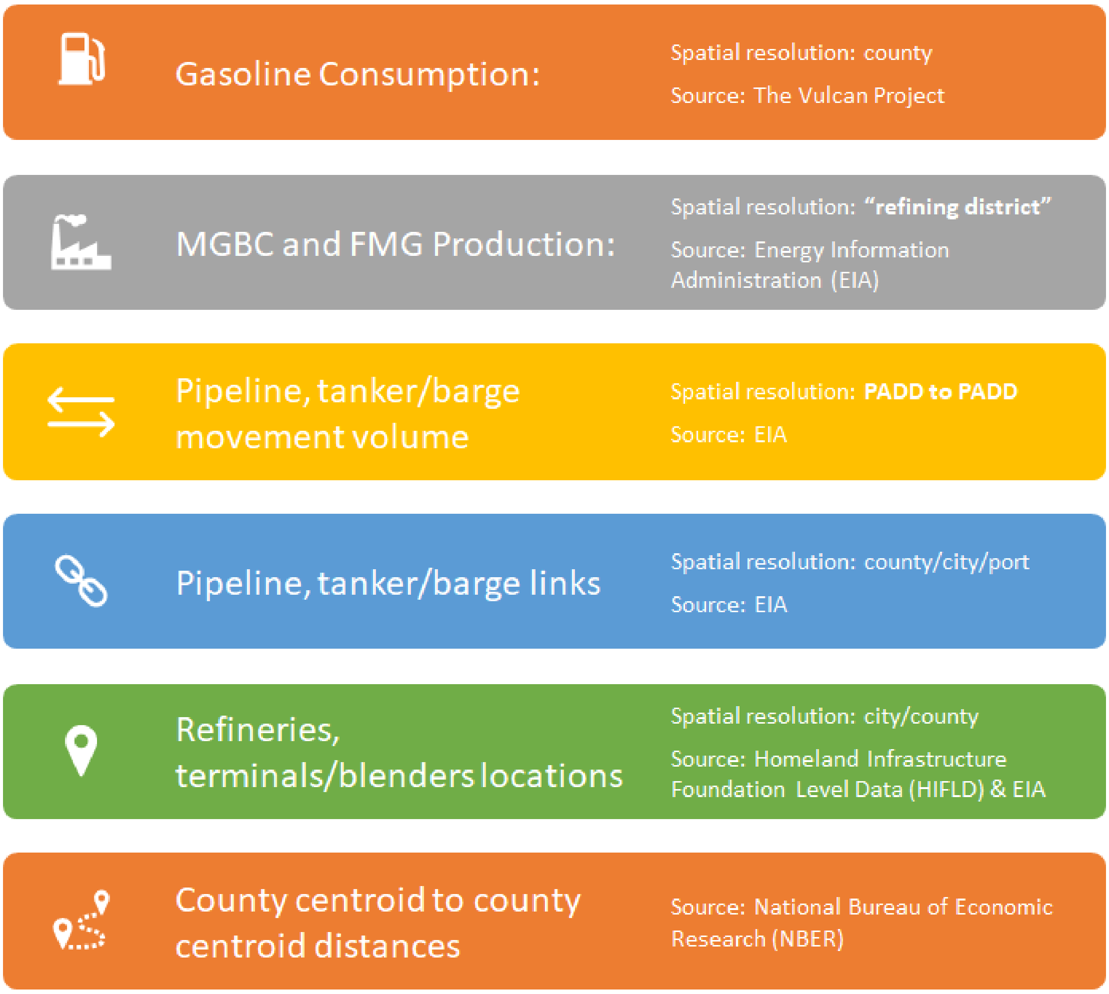


Figure 2. Data sources for each part of the supply chain and their associated spatial resolution.

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 (FMG) 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 MGBC allocation:

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

LINEAR OPTIMIZATION

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

- Two identical models are set up to break the supply chain
    1. Refinery to Blender Model (MGBC)
    2. Blender to Consumption County Model (FMG)
- Objective is to 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.

Objective:

$Min\ \sum_{ijk} C_{ijk} T_{ij} X_{ijk}$ (1)

Subject to:

$S_i + \sum_j X_{ijk}\ \geq\ D_i + \sum_i X_{ijk}$

$\cdots\ \forall i, j \in I, J$ (2)

$0.9 \times M_{vwk}\ \leq \sum_{ij} X_{ijk}\ \leq\ 1.1 \times M_{vwk}$

$\cdots\ \forall v, w, k\ \in\ V, W, K$ (3)

$X_{ijk}\ \geq\ 0$ (4)

Where,

$I\ =\ set\ of\ supply\ counties$

$J = set\ of\ demand\ counties$

$K = mode\ of\ transportation$

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

$C_{ijk} = cost\ of\ transporting\ from\ county\ i$
$to\ county\ j\ via\ transport\ mode\ k$

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

$S_i = production\ of\ product\ in\ gallons\ at$
$county\ i$

$D_i = consumption\ of\ product\ in\ gallons$
$at\ county\ i$

$V = origin\ PADD\ for\ intra - PADD\ movement$

$W = destination\ PADD$
$for\ intra - PADD\ movement$

$M_{vwk} = volume\ of\ gasoline\ in\ gallons\ moved$
$from\ PADD\ v\ to\ PADD\ w\ via$
$transport\ mode\ k$

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.

SCOPE 3 EMISSIONS

The final scope 3 emissions are the sum of the direct emissions from combustion of gasoline in the county (scope 1), the embodied emissions of moving the MGBC and FMG along the supply chain to the specific county and the refinery emissions per gallon combusted in a county (EPA, 2014; Pierru, 2007).

Embodied emissions are calculated as follows:

Embodied Emissions

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

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

Where,

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

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

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

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

$i = origin\ county$

$j = destination\ county$

$k = mode\ of\ transportation$

$n\ =\ other\ counties$

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

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

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

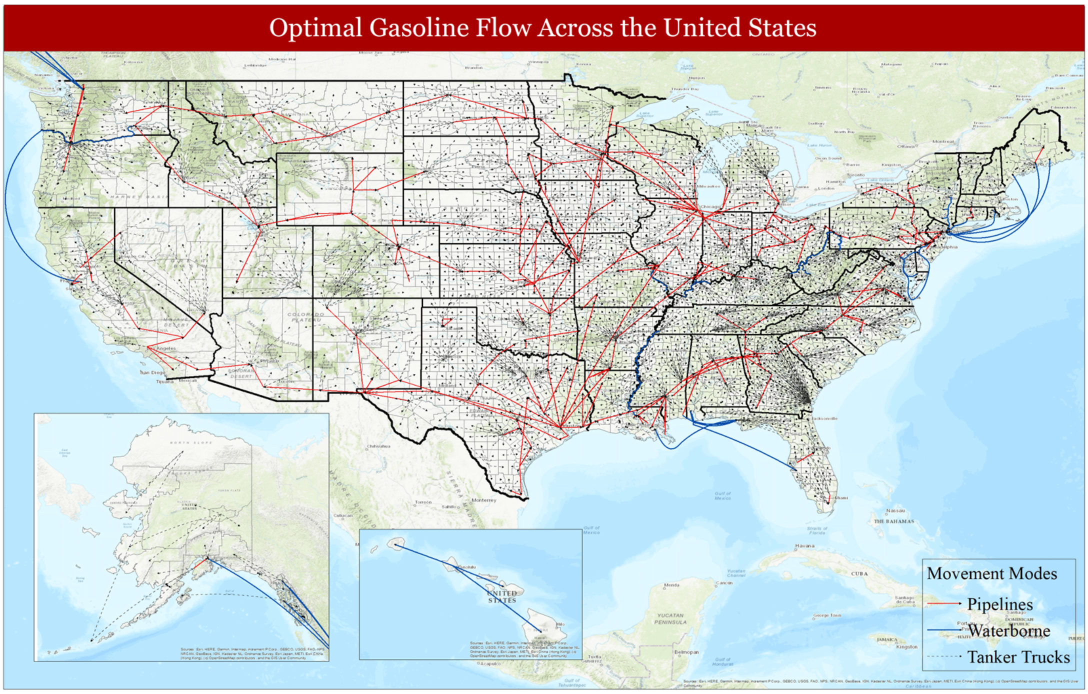
RESULTS

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 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 the same order. Within the top 10 counties of highest gasoline demand, only two counties have refining capability (Los Angeles, CA and Harris, TX). Other counties in the top 10 are serviced by refineries which are located in neighboring counties; Cook county, Illinois is serviced by a refinery in its neighboring county, San Diego, Orange, and San Bernardino counties in California are serviced by Los Angeles county and Kern county refineries. In contrast, Maricopa county, Arizona and Miami-Dade and Broward, Florida are serviced by out of state refineries. This increases the distance traveled and subsequently the embodied emissions in these counties' scope 3 emissions. Hence, the higher percentage differences in these counties scope 1 and scope 3 emissions.

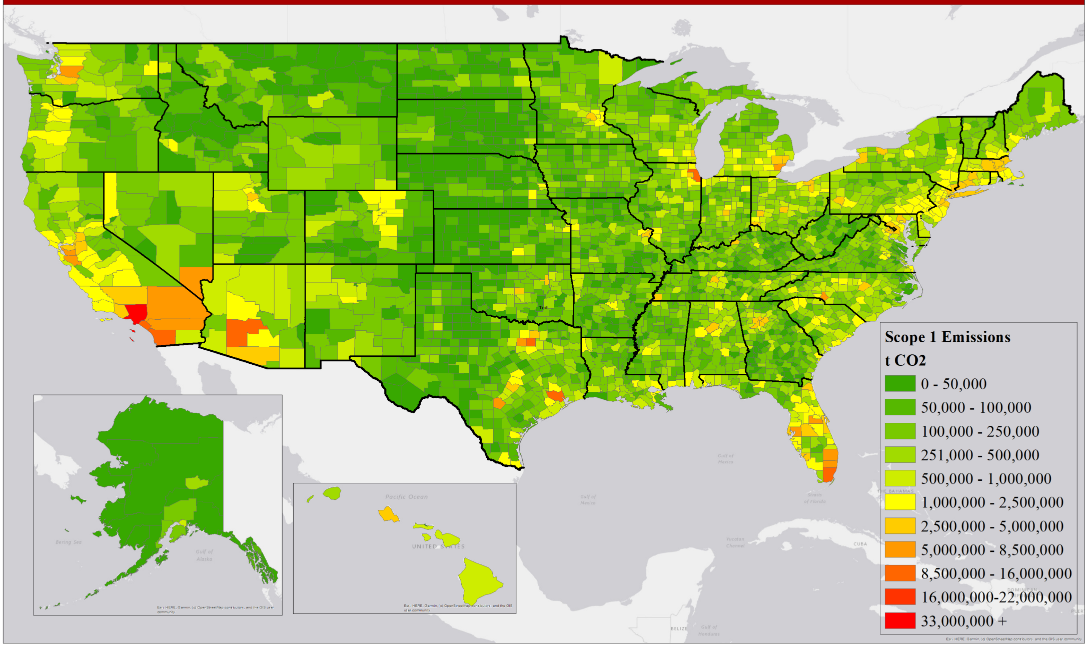
Scope 3 emissions increases the emissions for these top 10 counties by 32-68%.

Table 1. Scope 1 & scope 3 emissions of top

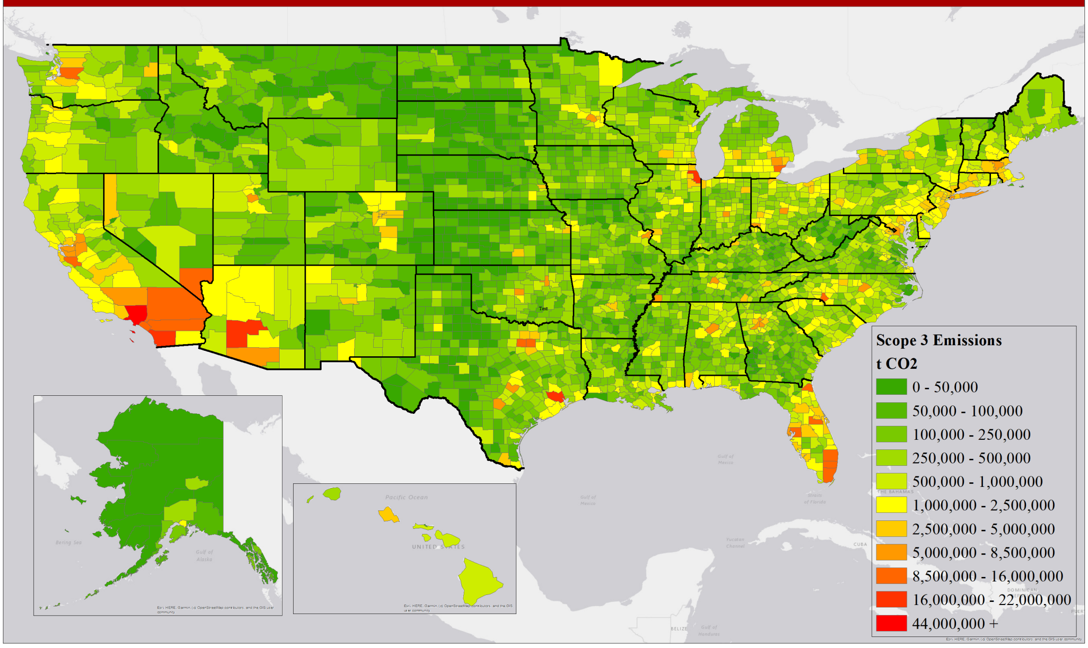
Top 10 Counties by Emissions				
	County	**State**	**Scope 1 Emissions (1,000 tons CO_2)**	**Scope 3 Emissions (1,000 tons CO_2)**
1	Los Angeles	CA	33,985.11	44,902.85
2	Harris	TX	15,506.68	21,040.18
3	Maricopa	AZ	12,980.20	19,488.20
4	Cook	IL	12,715.24	18,356.39
5	San Diego	CA	11,203.12	16,700.64
6	Orange	CA	11,060.31	15,254.94
7	Dallas	TX	9,245.18	13,541.55
8	Miami-Dade	FL	8,903.06	13,410.80
9	San Bernardino	CA	8,306.62	12,492.01
10	Broward	FL	7,358.57	12,384.71
	Mean		*13,126.41*	*18,757.23*
	Standard Deviation		*6,995.51*	*8,747.18*
	National Mean		***371.20***	***545.76***
	National Standard Deviation		***1,072.68***	***1,544.30***



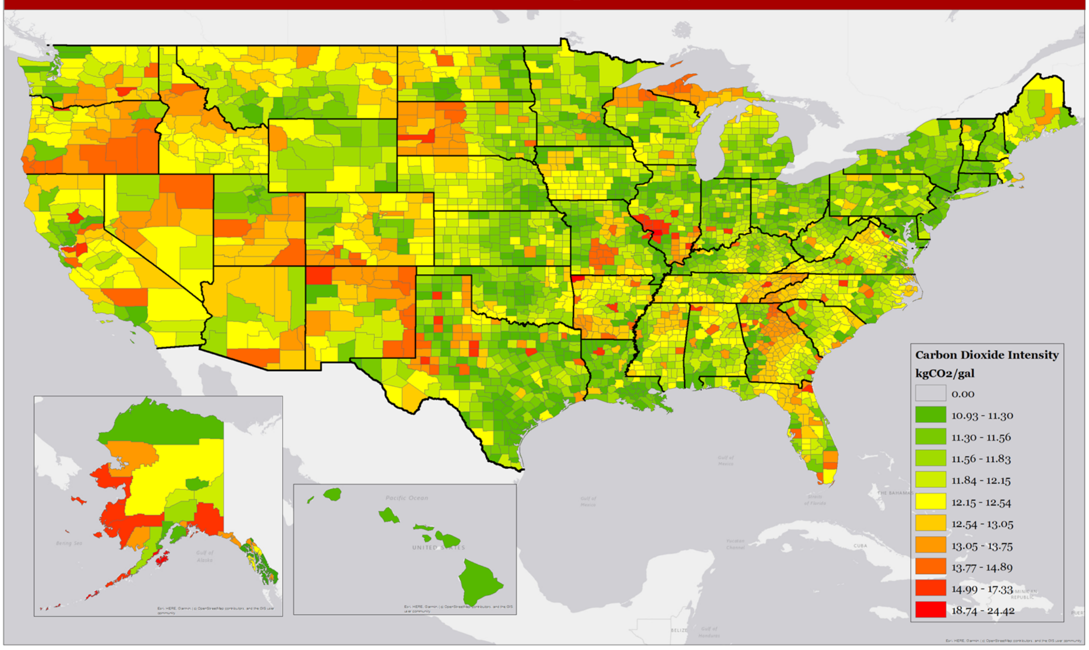
Scope 1 Emissions of Gasoline per County in the United States



Scope 3 Emissions of Gasoline 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 challenges in 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.

Kevin Gurney is a professor at Northern Arizona University. His training is in atmospheric science, ecology and public policy. Kevin currently research topics in carbon cycle science, climate science, and climate science policy. His recent projects involve simulation of the global carbon cycle using the inverse approach, quantifying fossil fuel CO2 from the building to global scale (the "Hestia", "Vulcan" and "FFDAS" projects), the relationships between US energy demand/supply and climate change, the linkages between terrestrial carbon exchange and climate variability, and the impacts of deforestation on climate. He has also worked extensively on climate policy and has been involved, for over 25 years, with the United Nations Climate Change Framework Convention and the Kyoto Protocol. In addition to carbon cycle science and policy, Kevin has worked on stratospheric ozone depletion, radionuclide dose assessment, energy systems modeling, and climate-economic modeling.

Richard Rushforth is an Assistant Research Professor in the School of Informatics, Computing, and Cyber Systems at Northern Arizona University. His research focuses on big data modeling of food, energy, and water systems to further the understanding of complex, coupled natural-human systems. His PhD is in Civil, Environmental, and Sustainable Engineering from Arizona State University. He also holds degrees from the University of Oxford (M.Sc. Waster Science, Policy, and Management) and the University of Arizona (M.S., Soil, Water, and Environmental Science; B.S., Environmental Science) as well as an M.B.A. from the W.P. Carey School of Business at Arizona State University.

Ben Ruddell, PhD, PE, is currently a Professor in and the Director of the School of Informatics, Computing, and Cyber Systems at Northern Arizona University, the President of Ruddell Environmental consulting, Chief Science Officer for Criticality Sciences Inc., and the Director of the FEWSION project. His PhD is in Civil and Environmental Engineering from the University of Illinois at Urbana-Champaign. He is a registered Professional Engineer in Arizona (Water Resources practice). His professional experience is in informatics, data science, systems engineering, and generally in the leadership of the interdisciplinary university enterprise. His professional goals are the advancement of the science and management of complex systems, and excellence in education in a university setting.

Deborah Huntzinger's research interests focus on improving the understanding of complex environmental systems and our ability to forecast their future variability. Her current research interests are in the integration and comparison of environmental remote sensing products, model estimates, and in situ data to advance the understanding of biospheric contributions, both spatially and temporally, to land-atmosphere carbon exchange. Dr. Huntzinger also has research focused on the use of industrial waste by-products to sequester industry generated CO2 emissions.

Nathan Parker is an assistant professor in the School of Sustainability, Arizona State University. He develops simulation models to shed light on the economic viability and environmental implications of alternative transportation fuels and biomass-based system. His research combines aspects of engineering, economics and geographic information systems (GIS). In addition, his work analyzes policies aimed at catalyzing transitions to renewable energy, working to improve both the methodologies and quality of policy analysis in this area.

ABSTRACT

Publicly accessible data has been used to construct a county-scale supply chain model of United States gasoline consumption and quantify the scope 3 CO_2 emissions from gasoline consumption. Our model tracks the movement of refined fuels from county of refinement to county of blending and eventually to county of consumption via multiple infrastructure networks -- pipelines, tankers, trains, and trucks. Where quantities of the fuel moved across different linkages and different transportation modes are known, they are used as is. However, for the vast majority of the country, the exact quantities of fuel moved between county of refining and county of blending or county of blending and county of consumption, as well as the mode of transportation, is not known with certainty. Linear optimization is used to model those links with constraints related to total supply and demand at lower spatial resolutions (State-level and Petroleum Administration for Defense (PAD) Districts). This is the first real attempt at a spatially-resolved scope 3 style CO_2 emissions data product specific to United States gasoline consumption. This model can improve understanding of the complex liquid fuel supply chain, and has significant implications for local policy. With a complete model of scope 3 CO_2 emissions, it is also possible to analyze how the differences between scope 1 and scope 3 emissions vary across the country. Finally, this model lays the foundation to model the evolution of the U.S. gasoline supply chain – its dependencies, critical linkages, and pinch points – and the evolution of scope 1 and scope 3 CO_2 emissions using the full extent of available public data.

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