Supplementary Information for

The Vulcan Version 3.0 High-Resolution Fossil Fuel CO$_2$ Emissions for the United States

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Table S1: Adjustment facters made to state-scale nonpoint fuel-specific FFCO$_2$ emissions via comparison to the EIA SEDS consumption data.

State	Res NG ratio (EIA/Vulcan)	Res Petrol ratio (EIA/Vulcan)	Com NG ratio (EIA/Vulcan)	Com Petrol ratio (EIA/Vulcan)
AK	1.00	0.85	SM^P	153.1
AL	1.00	0.75	1.10	4.85
AR	1.00	0.80	SM	474.6
AZ	1.03	1.02	CM$^\xi$	SM
CA	1.10	1.19	1.40	4.16
CO	1.01	1.03	SM	1.00
CT	1.01	0.77	1.22	0.90
DC	0.87	0.16	1.05	2.54
DE	1.00	1.00	1.09	1.77
FL	1.06	0.81	1.17	9.11
GA	0.94	0.93	1.12	4.09
HI	0.46	0.64	0.82	1.50
IA	0.96	0.48	1.09	8.04
ID	1.10	1.07	1.04	2.11
IL	0.96	0.49	0.95	0.66
IN	0.93	0.90	0.89	0.48
KS	0.87	1.07	1.00	14.2
KY	0.98	0.94	CM	CM
LA	1.07	0.86	1.51	324.9
MA	1.03	0.90	1.30	0.61
MD	1.00	0.84	0.92	0.59
ME	1.01	0.87	SM	1.29
MI	0.99	0.99	1.01	2.77
MN	0.92	0.97	1.08	0.34
MO	0.93	0.94	1.08	2.38
MS	1.02	0.90	1.14	8.26
MT	0.98	0.93	0.92	1.25
NC	1.03	0.71	1.03	0.94
ND	0.99	0.96	1.07	1.34
NE	0.97	0.99	0.98	SM
NH	1.03	0.78	1.22	1.55
NJ	0.97	0.58	1.11	1.11
NM	1.05	0.87	NM	1443.6
NV	1.12	0.40	CM	0.71
NY	0.99	0.96	5.15	0.52
OH	0.98	0.86	1.13	0.62
OK	0.94	0.93	1.08	156.7
OR	1.03	0.77	1.16	0.21
PA	0.97	0.94	1.05	1.00
RI	0.93	0.81	SM	0.072
SC	0.98	0.89	0.91	5.78
SD	0.93	0.86	SM	SM

TN	0.93	0.53	0.54	2.13
TX	0.92	0.52	1.18	116.3
UT	1.08	0.89	1.17	0.14
VA	0.97	0.95	1.01	1.10
VT	1.02	0.93	1.02	0.50
WA	1.13	0.64	SM	SM
WI	0.96	0.94	1.00	0.07
WV	0.97	0.46	3.35	73.7
WY	1.05	0.97	1.08	SM
US total	**0.99**	**0.83**	**1.46**	**0.97**

[ρ] No Vulcan nonpoint FFCO$_2$ emissions reported for this state. The EIA SEDS reported state total FFCO$_2$ was first debited by the Vulcan state point FFCO$_2$ and the remainder distributed to state counties according to the residential sector Vulcan nonpoint spatial distribution. In the case of the petroleum fuel category, the adjustments are made to distillate fuel only.

[ξ] In these cases, Vulcan nonpoint reported FFCO$_2$ emissions but for only a subset of legitimate counties (e.g. in Arizona, only Maricopa county reported nonpoint commercial NG FFCO$_2$ emissions). The EIA SEDS reported state total difference to the sum of the Vulcan point and nonpoint was distributed only to the unreported counties according to the residential Vulcan nonpoint spatial distribution.

Table S2: Building classification crosswalk table between the FEMA and DOE/EIA building types.

FEMA building code	FEMA building type	DOE/EIA aggregate type	DOE/EIA building sub-type code
RES1	Single family dwelling (e.g. House)	2	2
RES2	Mobile home	1	1
RES3A	Duplex	3	3+4
RES3A	Duplex	4	3+4
RES3B	3-4 units	4	4
RES3C	5-9 units	5	5
RES3D	10-19 units	5	5
RES3E	20-49 units	5	5
RES3F	50+ units	5	5
RES4	Temporary lodging (e.g. Hotel/motel)	18	18
RES5	Institutional dormitory (e.g. Group housing (military, college), jail)	13	13
RES6	Nursing home	17	17
COM1	Retail trade (e.g. Store)	25	25
COM2	Wholesale trade (e.g. Warehouse)	5	5+11
COM2	Wholesale trade (e.g. Warehouse)	11	5+11
COM3	Personal and repair services (e.g. Service station/shop)	26	26
COM4	Professional/technical services (e.g. Offices)	2	2+4
COM4	Professional/technical services (e.g. Offices)	4	2+4
COM5	Banks	26	26
COM6	Hospital	16	16
COM7	Medical office/clinique	8	8
COM8	Entertainment & recreation (e.g. Restaurants/bars)	15	15
COM9	Theaters (e.g. Theaters)	13	13
COM10	Parking (e.g. Garages)	1	1
IND1	Heavy (e.g. Factory)	324	324+333
IND1	Heavy (e.g. Factory)	333	324+333
IND2	Light (e.g. Factory)	313	313+314+315+316+321+322+323+326+327+337
IND2	Light (e.g. Factory)	314	313+314+315+316+321+322+323+326+327+337
IND2	Light (e.g. Factory)	315	313+314+315+316+321+322+323+326+327+337
IND2	Light (e.g. Factory)	316	313+314+315+316+321+322+323+326+327+337
IND2	Light (e.g. Factory)	321	313+314+315+316+321+322+323+326+327+337
IND2	Light (e.g. Factory)	322	313+314+315+316+321+322+323+326+327+337
IND2	Light (e.g. Factory)	323	313+314+315+316+321+322+323+326+327+337
IND2	Light (e.g. Factory)	326	313+314+315+316+321+322+323+326+327+337
IND2	Light (e.g. Factory)	327	313+314+315+316+321+322+323+326+327+337
IND2	Light (e.g. Factory)	337	313+314+315+316+321+322+323+326+327+337
IND3	Food/drugs/chemicals (e.g. Factory)	311	311+312+325
IND3	Food/drugs/chemicals (e.g. Factory)	312	311+312+325
IND3	Food/drugs/chemicals (e.g. Factory)	325	311+312+325
IND4	Metal/minerals processing (e.g. Factory)	331	331+332

IND4	Metal/minerals processing (e.g. Factory)	332	331+332
IND5	High technology (e.g. Factory)	334	334+335
IND5	High technology (e.g. Factory)	335	334+335
IND6	Construction (e.g. Office)	336	336
REL1	Church/non-profit	12	12
GOV1	General services (e.g. Office)	2	2
GOV2	Emergency response (e.g. Police/fire station/eoc)	7	7
EDU1	Grade schools	14	14
EDU2	Colleges/universities (does not include group housing	14	14

Table S3: Building type relationship between FEMA building types (see Table 4) and eQuest building types.

FEMA building code	FEMA building type	eQuest building code	eQUEST building type
RES1	Single family dwelling (e.g. House)	7	Multifamily_Low_rise_(exterior_Entries)
RES2	Mobile home	7	Multifamily_Low_rise_(exterior_Entries)
RES3A	Duplex	7	Multifamily_Low_rise_(exterior_Entries)
RES3A	Duplex	7	Multifamily_Low_rise_(exterior_Entries)
RES3B	3-4 units	7	Multifamily_Low_rise_(exterior_Entries)
RES3C	5-9 units	7	Multifamily_Low_rise_(exterior_Entries)
RES3D	10-19 units	6	Multifamily_High_rise_(interior_Entries)
RES3E	20-49 units	6	Multifamily_High_rise_(interior_Entries)
RES3F	50+ units	6	Multifamily_High_rise_(interior_Entries)
RES4	Temporary lodging (e.g. Hotel/motel)	5	Lodging_High-Rise_Hotel
RES5	Institutional dormitory (e.g. Group housing (military, college), jail)	1	Community_Center
RES6	Nursing home	3	Health_Long-term_Care_(Nursing_Home)
COM1	Retail trade (e.g. Store)	14	Retail_Stand-Alone_Structure
COM2	Wholesale trade (e.g. Warehouse)	17	Storage_Conditioned_(low_bay)
COM2	Wholesale trade (e.g. Warehouse)	17	Storage_Conditioned_(low_bay)
COM3	Personal and repair services (e.g. Service station/shop)	13	Retail_Service_Station-Convenience_Store
COM4	Professional/technical services (e.g. Offices)	8	Office_Bldg_2_story
COM4	Professional/technical services (e.g. Offices)	8	Office_Bldg_2_story
COM5	Banks	13	Retail_Service_Station-Convenience_Store
COM6	Hospital	2	Health_Hospital_(inpatient)
COM7	Medical office/clinique	4	Health_Medical_clinic_(out_patient)
COM8	Entertainment & recreation (e.g. Restaurants/bars)	10	Restaurant_Full_service_(full_menu)
COM9	Theaters (e.g. Theaters)	1	Community_Center
COM10	Parking (e.g. Garages)	18	Unknown_Custom_or_mixed_use
REL1	Church/non-profit	9	Religious_Worship
GOV1	General services (e.g. Office)	8	Office_Bldg_2_story
GOV2	Emergency response (e.g. Police/fire station/eoc)	8	Office_Bldg_2_story
EDU1	Grade schools	16	School_K-6_Elementary
EDU2	Colleges/universities (does not include group housing	16	School_K-6_Elementary

Table S4: NEI to HPMS road class crosswalk

NEI 2011 Road Type	HPMS Road Class
Rural Interstate: Total	Rural Interstate
Rural Other Principal Arterial: Total	Rural Principal Arterial – Other Freeways and Expressways
Rural Other Principal Arterial: Total	Rural Principal Arterial – Other
Rural Minor Arterial: Total	Rural Minor Arterial
Rural Major Collector: Total	Rural Major Collector
Rural Minor Collector: Total	Rural Minor Collector
Rural Local: Total	Rural Local
Urban Interstate: Total	Urban Interstate
Urban Other Freeways And Expressways: Total	Urban Principal Arterial - Other Freeways and Expressways
Urban Other Principal Arterial: Total	Urban Principal Arterial - Other
Urban Minor Arterial: Total	Urban Minor Arterial
Urban Collector: Total	Urban Major Collector
Urban Collector: Total	Urban Minor Collector
Urban Local: Total	Urban Local

Parking Area: Total	Urban Local

Onroad AADT gap-filling

Using the *Near Analysis* function in ArcGIS, road segments without AADT measurements are assigned the AADT value of the nearest road segment of the same road class with an AADT measurement. Road segments in need of gap-filling for which the nearest like-class is greater than 10 km away are gap-filled using the nearest road segment of the same class, without the urban/rural designation. All road classes, except for local roads, are gap-filled in this way. After all road segments in the road network (except local roads) are gap-filled for AADT data, total VMT are calculated for each road segment as

$$VMT = AADT * L \qquad\qquad\qquad (S1)$$

where *AADT* is the traffic volume (vehicles/day) and *L* is the road segment length (miles/segment).

Figure S1/Table S5 show the amount of VMT and road length gap-filling required in each state by the 6 merged basemap road classes (other than the urban and rural local classes which get a "flat" spatial structure). Far less gap filling is needed for the larger road classes, especially the arterials. The largest amount of gap-filling occurs on rural collector roads, followed by urban collector roads.
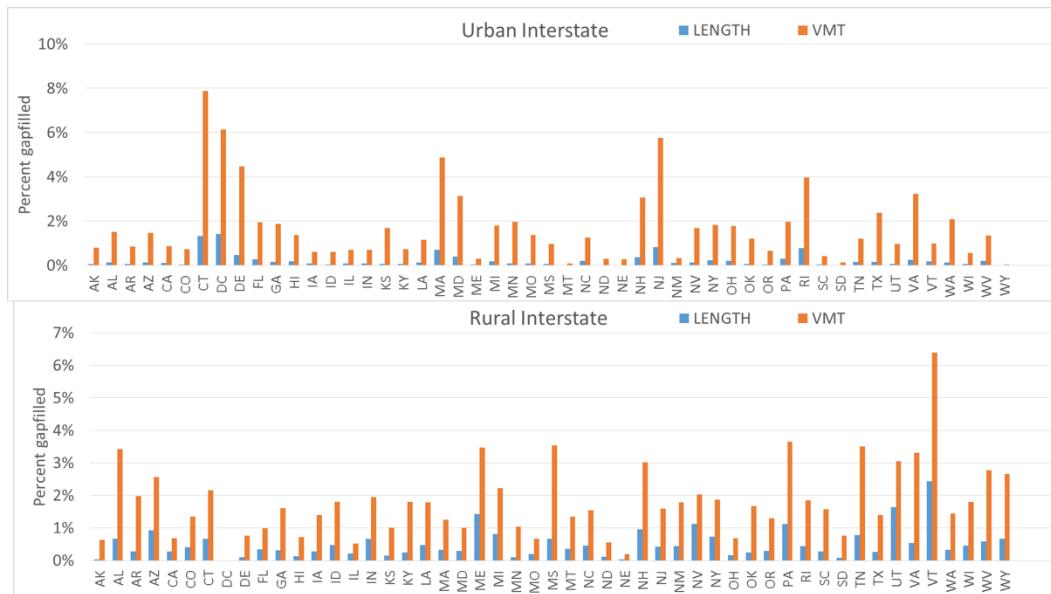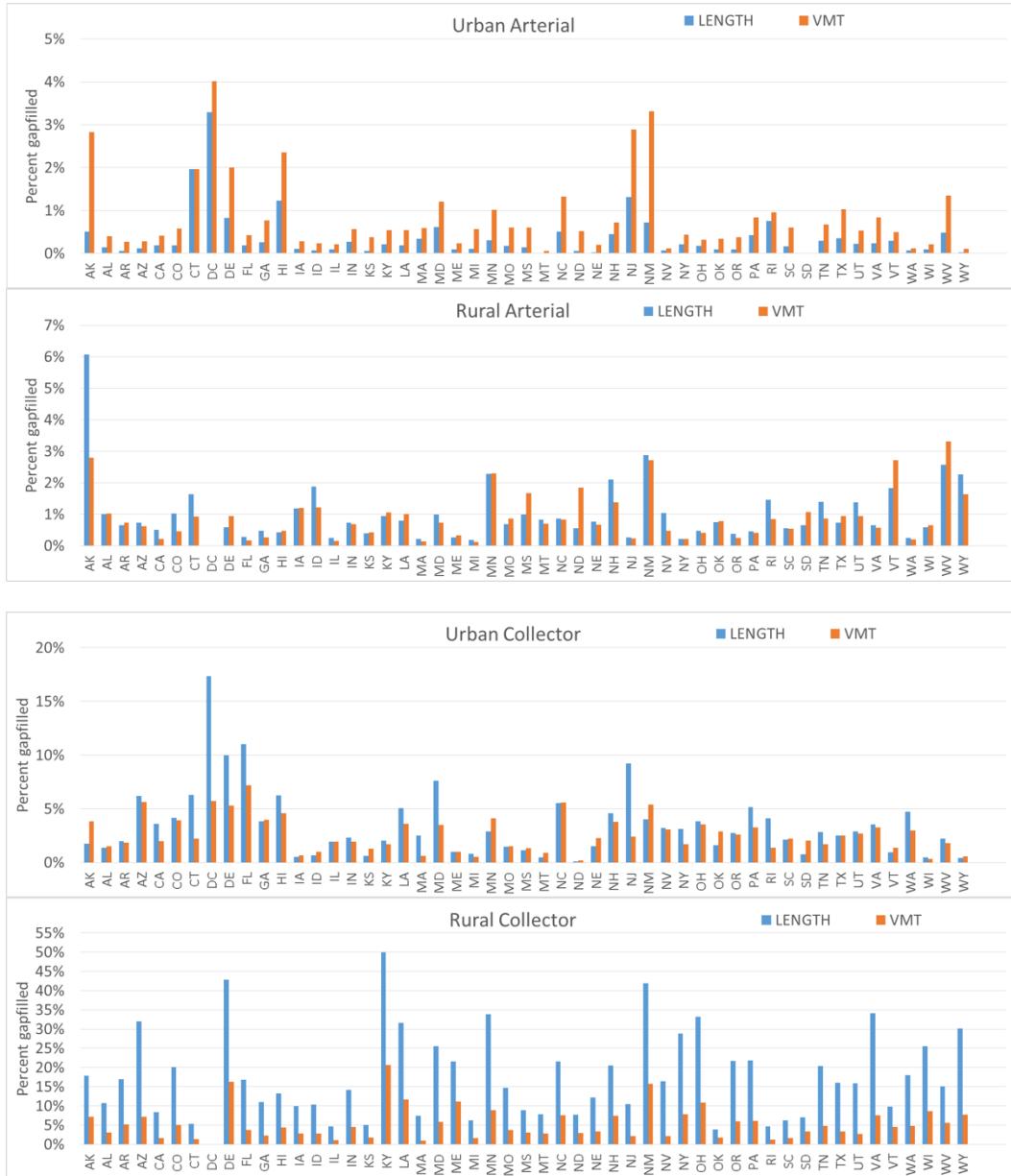
Figure S1: The percent of the total VMT that was the result of gap-filling, organized by state and non-local road class.

Table S5: Statistics on vehicle miles traveled (VMT) and road length gap-filling categorized by non-local road class.

	VMT - percent gapfilled						Road length - percent gapfilled				
	mean	sd	median	min	max		mean	sd	median	min	max
Rural Interstate	2.2%	1.3%	2.0%	0.2%	7.0%		0.6%	0.5%	0.4%	0.0%	2.5%
Urban Interstate	1.5%	1.5%	1.0%	0.0%	7.2%		0.2%	0.3%	0.1%	0.0%	1.4%
Rural Arterial	1.1%	0.9%	0.9%	0.2%	3.8%		1.1%	1.0%	0.8%	0.2%	6.3%
Urban Arterial	0.7%	0.8%	0.4%	0.0%	4.0%		0.3%	0.5%	0.1%	0.0%	3.3%
Rural Collector	6.5%	4.9%	5.3%	1.4%	23.7%		19.5%	11.9%	17.3%	4.1%	52.3%
Urban Collector	2.2%	1.4%	1.8%	0.1%	6.4%		2.7%	2.9%	2.0%	0.1%	17.3%

California/NEI vehicle/road class translation

The translation has two steps:

1) The FHWA VM2 data table contains the state-scale 2011 VMT on 14 road classes (FHWA 2011; 2013).[1] The FHWA VM4 data table contains the percentages of total VMT on 6 road classes across 6 vehicle classes.

The VMT specific to vehicle class and road class is estimated as follows:

$$VMT(s)_{v1}^{r1} = VMT(s)^{r1} \times p(s)_{v1}^{r2} \qquad \text{(S2)}$$

where s denotes a statewide variable, $r1$ is the 14-member road class, $r2$ is the 6-member road class, $v1$ is the 6-member vehicle class and p is the percentage of VMT.

Table S6 provides the crosswalk between the 14-member to the 6-member road class. With the state VMT for 6 vehicle classes on 14 road classes, one can generate a total for each vehicle class (across all rural and urban road classes).

Table S6: Crosswalk between the 14-member (the "rural" versus "urban" delimiters are not contained in the file but are implicit) and 6-member FHWA road classes.

FHWA 14-member classes	FHWA 6-member classes
Interstate (urban & rural)	interstate system
other freeways and expressways (urban & rural)	other arterials
other principal arterial (urban & rural)	other arterials
minor arterial (urban & rural)	other arterials
major collector (urban & rural)	other
minor collector (urban & rural)	other
Local (urban & rural)	other

2) The county-scale emissions by vehicle/road class is estimated as follows:

$$E(c)_{v1}^{r1} = \frac{VMT(s)_{v1}^{r1}}{\sum_{r1=1}^{14} VMT(s)_{v1}^{r1}} \times E(c)_{v2} \times 365 \times \frac{12.01}{44.01} \times 0.90718474 \qquad \text{(S3)}$$

where c denotes a county variable, and $v2$ is the 13-member vehicle class, final terms are conversion factors.

Table S7 provides the crosswalk between the 13-member vehicle class and the 6-member vehicle class.

Table S7: Crosswalk between the 13-member EMFAC and 6-member FHWA vehicle classes

FHWA 6-member vehicle class	EMFAC 13-member vehicle class
Passenger cars	LDA
Light Trucks	LDT1
Light Trucks	LDT2
Single-unit trucks	LHDT1
Single-unit trucks	LHDT2
Single-unit trucks	MDV
Single-unit trucks	MH
motorcycles	MCY
buses	OBUS
buses	SBUS
buses	UBUS
combination trucks	MHDT
combination trucks	HHDT

[1] Data available from https://www.fhwa.dot.gov/policyinformation/statistics/2011/vm2.cfm; https://www.fhwa.dot.gov/policyinformation/statistics/2013/vm4.cfm

Gap-filling onroad temporal data

The gap–filling availed of ten time profiles representing the twenty-four hour diurnal cycle for Monday, Friday, Saturday, Sunday, and Tues-Thurs in a six month summer (March - September) and a six month winter (September - March). Two seasons are used - Winter and Summer. Using four seasons resulted in an inability to gap fill some hours at some stations due to widespread missing data. Any hour for which traffic volume was not reported was gap-filled by matching the hour, season and day of the week to one of the ten average profiles and that average is used to fill the missing hour. When the number of values that go into generating the averages for the ten values falls below 6 (the max is 24), it is flagged with the number of members that were used. Figure S2 shows the number of instances where a single hour has less than or equal to 6 members for purposes of averaging. The maximum possible members in an average is 24 (6 months x 4 weeks). The total number of instances at each stations are 4380 (6 months x 4 weeks x 7 days x 24 hours) for a non-leap year. 2011 contained 888 individual hours across a total of 13 (an average of ~68/station) stations for which the averaging had less than 6 members. 2012 had 6768 such instances across 76 stations (about 89 per station) and 2013 had 1248 instances across 20 stations (an average of ~59 per station). Hence, there are numerous times where an average traffic volume value is constructed from a less than ideal number of averaging elements. 2012 appears to have the greatest number of instances in which averages are used that have less than 6 members to generate an average value.
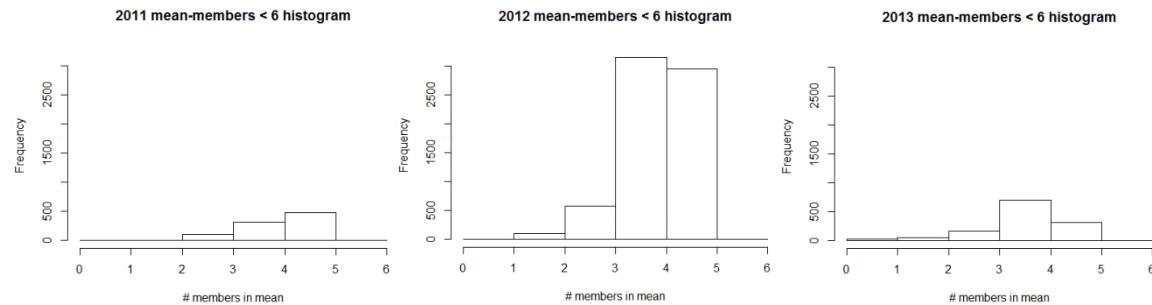
Figure S2: Frequency of hourly averages consisting of less than 6 averaging members

Alternative railroad spatial distribution

The sum of these unmatched railroad emissions within a given county are distributed along all rail segments using freight tonnage statistics (RITA, 2012). These statistics represent the freight tonnage range on different railroad segments defined as a class. For example, "class 1" segments carry 0.1 to 4.9 megatonnes of freight per unit length of railroad surface. A mean value of 2.5 MGT was used and that allowed for a distributional procedure based on these mean tonnage statistics. This would be expressed as:

$$TC^k(s) = TC^k \times \frac{FT^k(s)}{\sum_{s=1}^{S} FT^k(s)} \tag{S4}$$

where the total carbon emissions, *TC,* on segment, *s*, for the sector, *k*, (railroad surface in this instance) is the total railroad carbon emissions at the county level multiplied by the ratio of the freight tonnage, *FT*, on segment (where

the original tonnage per unit length is multiplied by the railroad segment length), *s*, to the county integral of freight tonnage.

Table S8. Relationship between the EIA SEDS sector/fuel codes and the sector/fuel categories used in the Vulcan multiyear scaling operation.

EIA/SEDS code	Vulcan sector/fuel	notes
NGRCB	Residential natural gas	Used for residential natural gas
PARCB	Residential petroleum	Used for all petroleum fuels
CLRCB	Residential coal	Used for residential coal
NGCCB	Commercial natural gas	Used for commercial natural gas
PACCB	Commercial petroleum	Used for all petroleum fuels
CLCCB	Commercial coal	Used for commercial coal
NGICB	Industrial natural gas	Used for industrial natural gas
PAICB	Industrial petroleum	Used for all petroleum fuels
CLICB	Industrial coal	Used for industrial coal
NGEIB	Electricity prod natural gas	Used for electricity production natural gas
PAEIB	Electricity prod petroleum	Used for all petroleum fuels
CLEIB	Electricity prod coal	Used for electricity production coal
NGACB	Transportation natural gas	Used for airport, onroad, nonroad
PAACB	Transportation petroleum	Used for onroad (other than gasoline), nonroad, CMV
CLACB	Transportation coal	Used for airport, onroad, nonroad, CMV – all coal
JFACB	Aviation jet fuel	Used for airport all petroleum
MGACB	Transportation gasoline	Used for onroad gasoline

Table S9. Vulcan v3.0 state-scale FFCO$_2$ emissions for years 2010-2015. Units: Mt/year.

State\year	2010	2011	2012	2013	2014	2015
AK	8.19	8.87	8.24	7.54	7.38	7.69
AL	45.84	45.11	43.31	42.78	44.02	42.70
AR	18.21	18.64	18.77	19.14	19.14	16.56
AZ	30.01	29.49	29.29	30.39	29.83	29.76
CA	105.93	104.00	104.27	105.61	103.68	104.59
CO	33.34	31.01	30.92	31.74	32.24	31.89
CT	10.46	10.00	9.69	10.14	10.24	10.61
DC	1.31	1.24	1.09	1.14	1.24	1.23
DE	3.68	4.01	4.20	4.38	4.59	4.45
FL	82.88	77.43	75.15	75.24	77.13	78.29
GA	51.72	47.70	42.43	42.06	43.34	42.23
HI	5.24	5.40	5.16	5.12	4.97	4.94
IA	25.23	24.41	23.00	23.22	23.47	21.84
ID	5.74	5.66	5.69	6.19	6.05	6.69
IL	71.57	70.42	66.60	70.47	71.45	67.34
IN	60.98	59.16	55.89	58.32	59.65	55.89
KS	22.19	21.46	20.28	21.57	21.88	19.78
KY	40.19	39.62	37.25	37.26	37.42	35.15
LA	50.44	51.96	48.64	47.77	46.80	47.29
MA	22.73	21.68	19.61	20.38	20.16	20.68
MD	25.97	20.97	19.95	19.27	19.86	19.45
ME	5.94	5.76	5.27	5.42	5.37	5.36
MI	49.80	47.99	46.82	49.40	49.98	49.80
MN	34.41	33.96	32.74	34.01	35.00	33.04
MO	40.56	40.84	38.76	39.93	39.64	37.47
MS	18.82	17.22	17.56	17.27	17.97	18.31
MT	9.63	8.90	8.49	8.91	8.98	8.95
NC	47.26	42.62	41.34	44.18	44.82	42.29
ND	12.27	12.60	13.72	13.30	13.64	13.21
NE	14.41	14.66	14.16	14.84	14.51	14.01
NH	4.76	4.70	4.28	4.19	4.30	4.36
NJ	26.72	26.08	24.43	24.92	26.03	26.11
NM	15.27	15.68	15.29	15.24	14.25	14.62

NV	15.08	13.17	13.13	13.72	14.69	12.77
NY	55.77	51.98	51.25	52.02	54.28	53.22
OH	78.19	75.07	70.23	72.57	73.45	68.69
OK	31.96	32.31	31.77	31.10	31.51	30.47
OR	11.98	10.86	10.88	11.62	11.30	11.37
PA	78.33	74.85	71.63	74.53	74.17	70.96
RI	5.28	4.83	4.60	4.81	5.25	5.10
SC	24.74	23.62	22.22	21.11	22.33	22.08
SD	3.90	3.70	3.84	3.86	3.94	3.60
TN	32.05	31.06	29.68	29.40	30.70	28.88
TX	146.50	150.20	144.56	149.70	151.94	150.98
UT	20.44	20.63	20.17	21.59	21.38	20.80
VA	29.81	27.35	26.78	28.69	28.40	28.26
VT	1.80	1.76	1.68	1.76	1.78	1.84
WA	20.69	19.23	19.27	20.76	20.02	20.85
WI	32.93	32.03	29.42	32.26	32.49	31.99
WV	25.18	25.02	23.32	23.86	25.37	23.25
WY	21.89	22.30	22.72	23.21	22.54	21.97
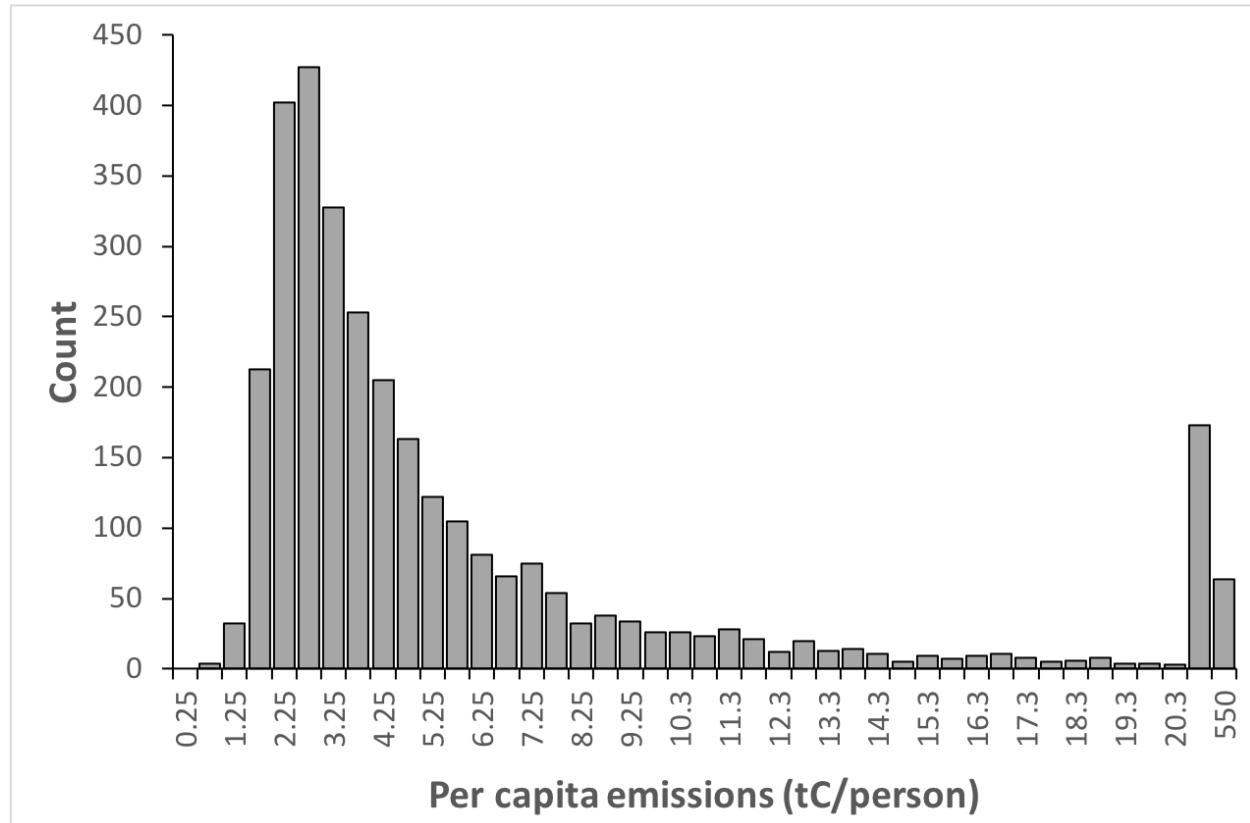
Figure S3: Frequency distribution of the state-scale per capita total FFCO$_2$ emissions.