Supplementary Information for "A bottom up approach to on-road CO_2 emissions estimates: improved spatial accuracy and applications for regional planning."

Authors: Conor K. Gately,* Lucy R. Hutyra, Ian S. Wing, Max N. Brondfield

Department of Earth and Environment, Boston University, 685 Commonwealth Avenue, Boston, MA, 02215

*Corresponding author: Conor K. Gately, email: cgately@gmail.com

Pages: 12

Figures: 3

Tables: 1

Supporting Information

All data used in this study are publically available, with sources as indicated in the references section. Gridded results of our HPMS-based model are available for download at http://people.bu.edu/lrhutyra/Data.html or from the corresponding author directly, as comma-delimited files containing emissions estimates at 1km^2 and 0.1 degree grid scales.

All figures and spatial data were projected using the NAD1983 State Plane Massachusetts Mainland FIPS 2001 Lambert Conformal Conic Projection.

1. Detailed Methodology of HPMS-based on-road CO_2 emissions model

Calculate VMT by functional class and county

The HPMS is a national database managed by the Federal Highway Administration (FHWA) that contains data on annual average daily traffic volumes (AADT) and centerline mileage for all Federal-Aid roads and most other major and minor roads. We obtained annual VMT for each road section in the HPMS by multiplying the average daily traffic volume by the length of the road section in miles and then multiplied by 365 days. The FHWA requires that the AADT values submitted by each state be adjusted prior to submission to take into account both weekday/weekend and seasonal variations in traffic volumes on the road section. Thus the AADT reported in the HPMS reflects an average daily traffic volume for any day in the calendar year, independent of day of the week or month of the year. While this limits the use of the data for analyses at shorter time scales, it allows for a straightforward estimation of annual statistics for each road section without having to account for weekly and monthly variations.

The road sections in the HPMS are not geo-coded, and consequently we were not able to assign our annual VMT estimates directly to a map of the road network. However, functional class and county were available for each road section, with each functional class identified as urban or rural depending on if the road section passes through a Census Bureau Urbanized

Area or Urban Cluster. Therefore we chose to aggregate our roadway-scale VMT to the county scale, stratified by the 12 HPMS functional classes.[1] Since our roadway-scale HPMS data does not include all of the VMT that occurred on local roads it was necessary to use a downscaling approach to account for emissions from these roads. We allocated state-level data from FHWA[2] on VMT for Rural Minor Collectors and Rural and Urban Local roads to each county using the county's fraction of total state VMT as calculated from the HPMS dataset for each year.

Disaggregate VMT by Vehicle Type

As on-road CO_2 emissions are a product of fuel combustion, and the rate of emissions is a function of fuel type,[3] our intermediate goal was to estimate diesel and motor gasoline fuel consumption for each functional class and county. First we partitioned annual vehicle miles travelled amongst five different vehicle types: passenger cars, passenger trucks (which includes SUVs, vans and pickup trucks), buses, single-unit trucks and combination trucks. State-level data on the distribution of VMT among different vehicle types is available for the years 1993 through 1999 and for 2009 and 2010.[4] A comparable national average distribution for the years 1980 to present exists as well.[5] However, when we compared the state and national distributions for 1993 through 1999 we observed that Massachusetts had significantly lower fractions of passenger truck and heavy truck VMT across all road types relative to the national average. Since this difference would strongly affect our fuel estimates, we chose to use the state-level data for the available years and to estimate values for the years prior to 1993 and after 1999. For our model years 1999 through 2008 we interpolated linearly between the state-level distributions for 1999 and 2009; for years prior to 1993, we applied the 1993 distribution for all years.

Estimate fuel consumption by vehicle type, functional class, and county.

We used the national average fuel economy for each vehicle type for each year[5] to estimate fuel consumption for each roadway functional class, county and year. Fuel consumption was calculated as the quotient of distance travelled and average fuel economy. We assumed all fuel consumption by passenger cars and passenger trucks was motor gasoline, all fuel consumption by buses and combination trucks was diesel fuel, and that fuel consumption for single-unit trucks was 23% motor gasoline and 77% diesel fuel. The fuel shares for single-unit trucks were taken as an average value across the study period using reported fuel consumption by medium and heavy vehicles obtained from the 2010 Transportation Energy Data Book.[6]

Calculate CO_2 emissions by functional class and county

We used emissions factors to estimate the CO_2 emissions produced by the fuel consumption for each vehicle type. Fuel consumption was converted to CO_2 emissions using the emission factors of 8.91 kg CO_2 per gallon gasoline and 10.15 kg CO_2 per gallon diesel fuel.[3] We then aggregated CO_2 emissions from both fuels to obtain total emissions for each functional class of road at the county scale.

Assign emissions to road network

To assign emissions to a map of the road network we used the 2009 GIS Road Inventory provided by the Massachusetts Department of Transportation[7] which provides the length and functional class of almost every road section in the state. We recognize that the road network has changed in extent since 1980, but FHWA records for Massachusetts indicate that total centerline mileage increased only 6.9%, from 33,777 in 1980 to 36,105 in 2008.[8] We decided to use the Road Inventory for our analysis, as it is the only geo-referenced dataset that covers all Massachusetts roads. However, we note that the use of this dataset might introduce potential errors due to the allocation of historical emissions across the contemporary road network.

To assign CO_2 emissions to each road we calculated the total centerline mileage of each functional class of road in each county, and then divided our relevant CO_2 emissions by this mileage to generate average per-mile CO_2 emissions. These average per-mile emissions were then assigned by functional class and county to the road network for each year in the study period.

Aggregate road-level emissions to other spatial scales

For comparability with other CO_2 emissions inventories, we aggregated our roadway-scale emissions to multiple scales: a 1km x 1km grid, a 0.1 x 0.1 degree grid, and summed to the level of local towns. The 1km grid cells provided a high-resolution display of the emissions data in a gridded format. The 0.1 degree grid aggregation provided for a direct comparison with the EDGAR and Vulcan inventory products. The town level data was used in regression analysis of the spatial and temporal correlations between emissions and population density, as population data for the full time series was only available at the town scale. All figures and spatial data were projected in ESRI ArcGIS 10, using the NAD1983 State Plane Massachusetts Mainland FIPS 2001 Lambert Conformal Conic Projection.

2. Cell-by-cell comparison of HPMS and Vulcan emissions estimates for 2002

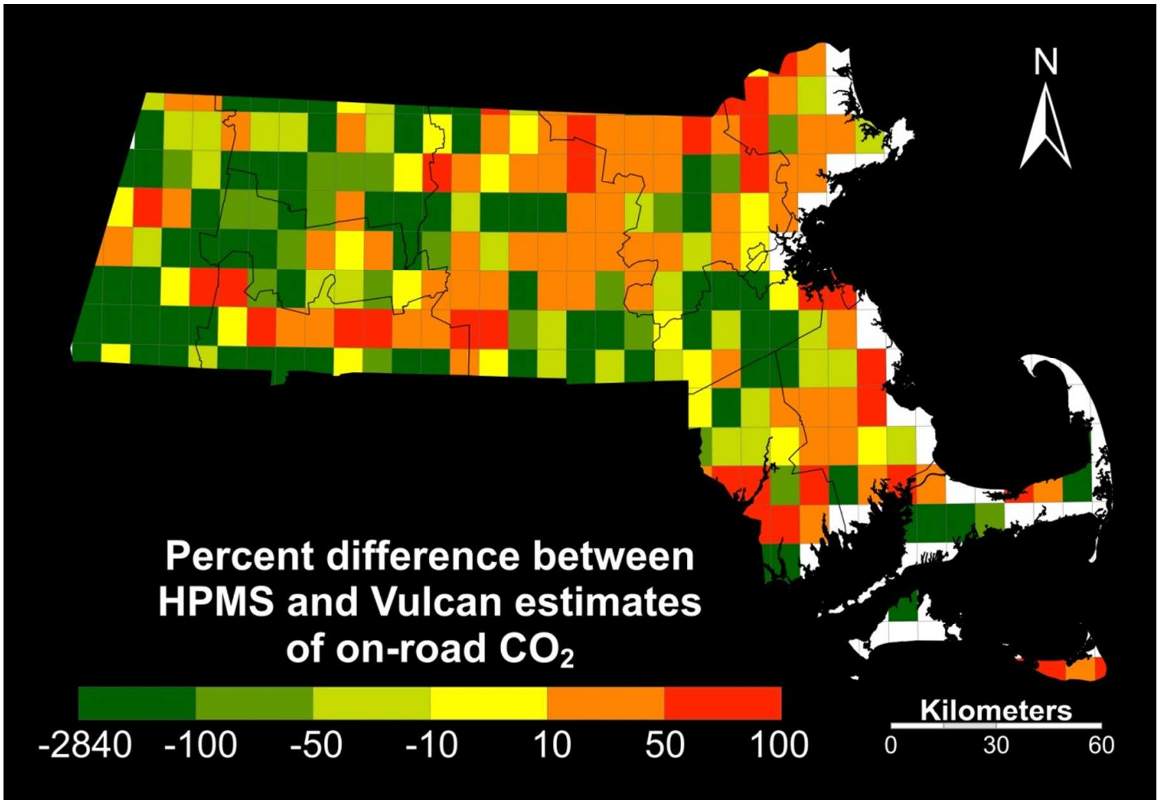

Figure S1. Percent differences between HPMS model CO_2 estimates and Vulcan Product estimates for the year 2002, at 0.1 degree grid scale. Values calculated as: (HPMS – Vulcan) / HPMS *100; positive values indicate grid cells where HPMS estimates exceed Vulcan estimates. White grid cells indicate cells where Vulcan reports zero emissions. This is a result of the re-gridding process used by Vulcan to transform the original $10km^2$ gridded results to the 0.1 degree grid.[8] Note that the HPMS model produces higher emissions estimates than Vulcan in urban areas, whereas the opposite is true in more rural or less populated areas.

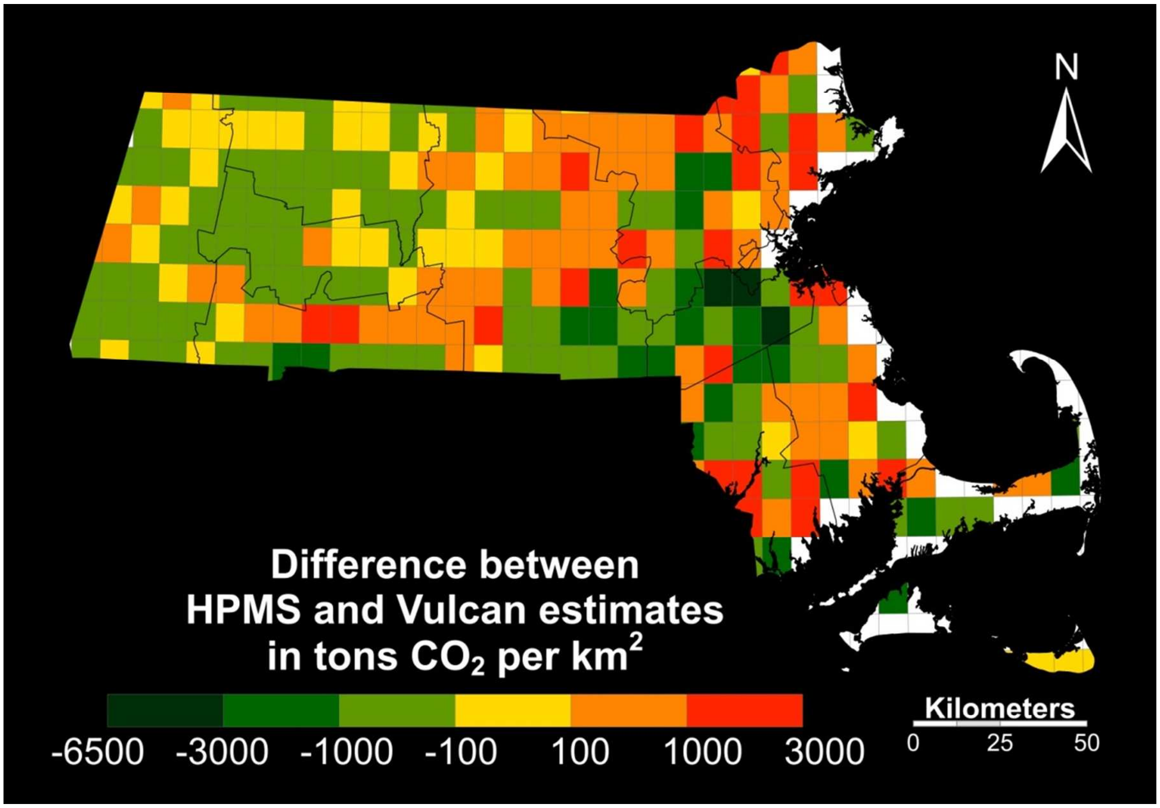

Figure S2. Absolute difference in estimates of tons CO2 per square kilometer between HPMS and Vulcan. Positive values indicate cells where our HPMS model predicts higher CO2 emissions than the Vulcan Product. The spatial distribution of raw difference between the two models is similar to that of the percent difference, with HPMS producing higher estimates in urban areas relative to Vulcan (north central, north eastern and south eastern areas), and Vulcan producing higher emissions estimates in rural areas (western regions and parts of south central and south eastern areas).

Uncertainty Estimates

The uncertainty associated with annual average daily traffic (AADT) values reported in HPMS is characterized by the confidence intervals and precision levels reported in Chapter 6 of the HPMS Field Manual.[10] These confidence intervals vary by functional class, and take the form of a combined confidence interval and precision level in the form of A-B, where is A is the probability that the value falls within B percent of the true value. For example a reported uncertainty of 90-10 would mean that 90 percent of the time the reported value will be within 10% of the true value.

However, as each functional class of road has a different confidence interval and precision level associated with its AADT estimates, these cannot be directly combined into an overall estimate of the uncertainty in AADT for the whole HPMS data set. To standardize this uncertainty, Mendoza et al.[11] converted each HPMS confidence interval / precision level into one-sigma percent uncertainties as quoted below:

"…the stated confidence interval and precision level were combined into a single estimate of uncertainty as follows:

$U_x = V_x / S_x$

Where U_x is the uncertainty percent value associated with road type; V_x is the percent variation from the true value for road type (10 for 90-10); and S_x is the number of standard deviations within a normal distribution that is within variation of the true value for road type ("90" for 90-10)."

Source: Mendoza et al.[11]

Using this method Mendoza et al. estimate one-sigma percent uncertainties for Rural Interstates and Rural Principal Arterials of ±3.04%, for Rural Minor Arterials of ±6.08%, and for all other functional classes of road of ±7.8%. These are one standard deviation percent uncertainties, which represent roughly a 68.3% confidence interval. To estimate a broader confidence interval we also calculated a two-sigma uncertainty, equivalent to a 95.4% confidence interval. To do this, we doubled the one-sigma percent uncertainties reported by Mendoza et al.[11] We used both the one-sigma and two-sigma percent differences to calculate upper and lower estimates of AADT for each road in our dataset. We then ran our model using these values to produce upper and lower estimates of CO_2 emissions for each road section. The one-sigma shifted AADT produced emissions estimates that ranged from ±7.4% to ±7.6% relative to our original CO_2 estimates. The two-sigma shifted AADT produced emissions estimates that ranged from ±14.7% to ±15.2% relative to our original estimates. Both of these ranges correspond well with the empirical estimates of AADT uncertainty by Ritchie[12] and Gadda et al.[13], and suggest that the FHWA confidence/precision levels provide a reasonable basis for assessing the uncertainty of CO_2 emission estimates generated from the AADT values reported by HPMS. We report the upper and lower bound estimates of CO_2 emissions from our HPMS model in figure S3.

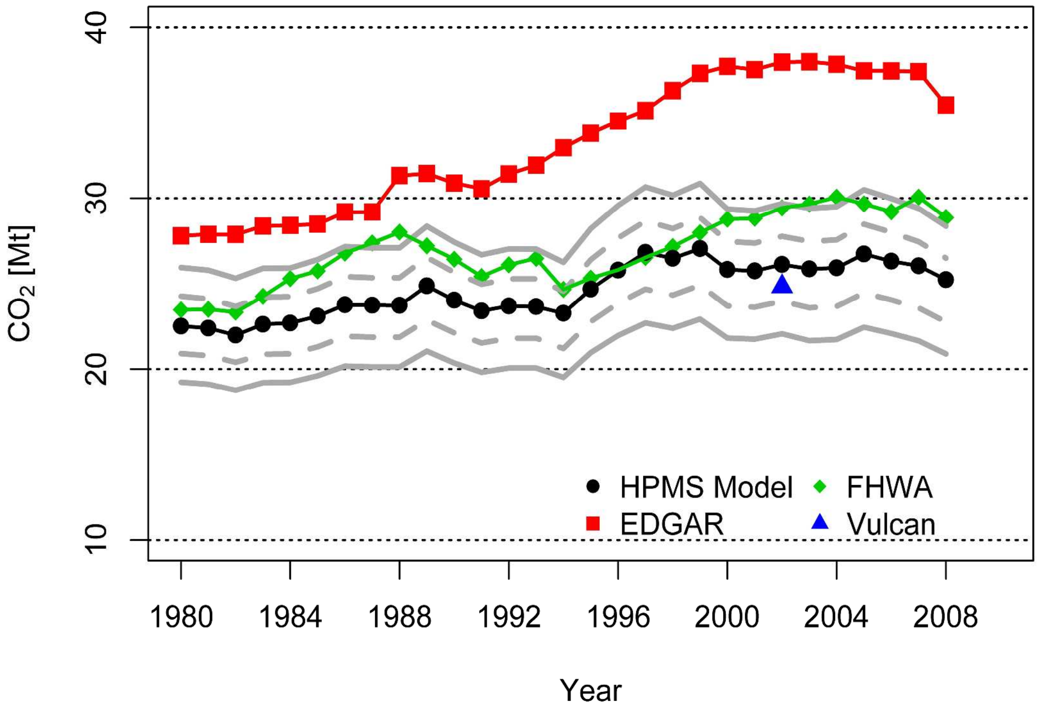

Figure S3. Plot of CO_2 estimates from HPMS, FHWA, EDGAR and Vulcan. Solid gray line shows upper and lower estimates from HPMS model run with two-sigma percent changes in AADT. Dashed gray line shows upper and lower estimates from one-sigma percent change in AADT.

Results of panel regression.

Number of obs.	10150		
F(389, 9760)	1513.35	R-squared	0.933
Prob. > F	0.0000	Root MSE	104.29
Variable	**Coefficient**	**Standard Error**	**t**
pop / km^2	-26.684	2.971	-8.980
pop / km^2 > 10	13.842	3.296	4.200
pop / km^2 > 50	10.577	1.531	6.910
pop / km^2 > 100	3.580	0.463	7.740
pop / km^2 > 200	0.036	0.197	0.180
pop / km^2 > 500	-0.418	0.100	-4.170
pop / km^2 > 1000	-0.713	0.095	-7.530
pop / km^2 > 2000	-0.346	0.082	-4.200
pop / km^2 > 3000	0.130	0.060	2.170
pop / km^2 > 4000	-0.243	0.073	-3.340
pop / km^2 > 5000	0.140	0.073	1.900
pop / km^2 > 6000	0.120	0.031	3.880
constant	775.924	85.122	9.120

Table S1. Results of panel regression analysis. Dependent variable is tons of CO_2 emissions per mile of road. Town and year fixed effects not shown.

References for Supplemental Information

1. *Highway Performance Monitoring System Field Manual, Chapter 4*; Federal Highway Administration: Washington, DC, 2005; http://www.fhwa.dot.gov/ohim/hpmsmanl/chapt4.cfm

2. *Highway Statistics Series, Table VM-2*; Federal Highway Administration: Washington, DC, 1980 – 2010. http://www.fhwa.dot.gov/policyinformation/statistics.

3. *Documentation for Emissions of Greenhouse Gases in the U.S. 2005, Table 6-1. DOE/EIA-0638 (2005)*; Energy Information Administration: Washington, DC, 2007.

4. *Highway Statistics Series, Table VM-4*; Federal Highway Administration: Washington, DC, 1993 – 1999; 2009 – 2010. http://www.fhwa.dot.gov/policyinformation/statistics.

5. *Highway Statistics Series, Table VM-1*; Federal Highway Administration: Washington, DC, 1993 – 1999; 2009 – 2010. http://www.fhwa.dot.gov/policyinformation/statistics.

6. *Transportation Energy Data Book, 30th Edition*; Department of Energy, Energy Efficiency and Renewable Energy, Washington, DC, 2011; http://cta.ornl.gov/data/index.shtml

7. *Road Inventory File;* Massachusetts Department of Transportation 2009; http://www.massdot.state.ma.us/planning/Main/MapsDataandReports/Data/GISData.aspx

8. The Vulcan Project: README – Vulcan filesets and Regridding information. http://vulcan.project.asu.edu/pdf/fileset.readme.v2.2.pdf

9. *Highway Statistics Series, Table HM-20*; Federal Highway Administration: Washington, DC, 1980 – 2010. http://www.fhwa.dot.gov/policyinformation/statistics.

10. *Highway Performance Monitoring System Field Manual, Chapter 6*; Federal Highway Administration: Washington, DC, 2005; http://www.fhwa.dot.gov/ohim/hpmsmanl/chapt6.cfm

11. Mendoza, D.; Gurney, K.R.; Geethakumar, S.; Chandrasekaran, V.; Zhou, Y.; Razlivanov, I. Implications of uncertainty on regional CO_2 mitigation policies for the U.S. onroad sector based on a high-resolution emissions estimate. *Energy Policy,* (In Press)

12. Ritchie, S.G. A statistical approach to statewide traffic counting. *Transportation Research Record No. 1090*, Transportation Research Board, Washington, DC, 1986, 14-21.

13. Gadda, S.; Magoon, A; Kockelman, K.M. Estimates of AADT: Quantifying the uncertainty. Proceedings of the 86th Annual Meeting of the Transportation Research Board, Washington DC, 2007.