A Set of Comparable Carbon Footprints for Highway Travel in Metropolitan America

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Abstract

The authors describe the development of a set of carbon dioxide emissions estimates for highway travel by automobile, truck, bus and other public transit vehicle movements within the nation's 100 largest metropolitan areas, in calendar year 2005. Considerable variability is found to exist across metropolitan areas when these greenhouse gas emissions are measured on a per capita and a per gross metropolitan product (GMP) basis. Least square regression modeling shows a relationship between emissions per capita and per GMP with truck traffic share, transit share, employment density, population dispersion within the metro area, and GMP per capita. As a result many of the nation's largest metropolitan areas tend to have lower CO2 emissions per capita and per GMP than smaller and more recently developed metro areas.

1. INTRODUCTION

Government concerns over both energy security and global warming have taken center stage as public policy issues in many developed nations in the last few years. At the heart of this concern is the heavy dependence on petroleum as an energy source, and in particular the worldwide dependence on petroleum as its transportation fuel. Much of the travel activity associated with this fuel use occurs within urbanized areas, and urban populations are expected to continue to grow over the next few decades. In the United States the transportation sector has been estimated to account for 33 percent of the nation's carbon dioxide (CO_2) emissions and to be responsible for over forty percent of the growth in its total, multi-sector carbon emissions between 1980 and 2007 (EIA, 2007). According to the US Energy Information Administration's *Annual Energy Outlook 2009*, and despite expected improvements in vehicle energy efficiency and a growing use of alternative fuels, CO_2 emissions from US transportation are forecast to grow at 0.4 percent annually (EIA, 2009). This would result in a 10 percent net increase by 2030, at a time when the Intergovernmental Panel on Climate Change and governments around the world are calling for reductions in greenhouse gas (GHGs) emissions (IPCC, 2007).

While other GHGs are also important in the transportation sector, notably methane (CH_4) and nitrous oxide (N_2O) emissions, CO_2 emissions are estimated to account for over 95% of the global warming potential from transportation sector sources (EIA, 2007). With these statistics as background, the present paper builds on a recent study for the Brookings Institution that was commissioned to investigate the following questions (Brown, et al, 2008):

- just how much CO_2 is being produced within the largest U.S. metropolitan areas (metros), and how much CO_2 emissions rates vary both across metros;
- whether large metros are more or less polluting on a per capita and a per dollar basis than smaller metros or non-metro areas; and
- whether such differences both within and between metropolitan areas can be explained in terms of variables that are amenable to GHG-reducing policy instruments: with a particular emphasis on variables that reflect differences in urban form.

The analysis is aggregate and cross-sectional in nature, in that it computes emissions rates estimated for complete metropolitan areas for a given calendar year. The results for year 2005 are the focus of this present paper, while year 2000 emissions were also computed as part of a larger carbon footprinting study (Brown, et al, 2008). The principal reason for the approach taken was the perceived need to develop a set of carbon emission estimates that are derived in a consistent manner, using the same database and methodology, for a large number of different metropolitan areas: and to do so for the rapidly growing volumes of comparatively low miles per gallon truck, as well as auto, travel.

This current paper extends the original study in two ways. First, to complete the highway travel picture, CO_2 emissions from those public transit trips, principally buses, which use the nation's highways were also computed. Second, the original study measured only the "direct" or tailpipe emissions associated with these metropolitan area traffic movements. These are the emissions that are most likely to be influenced by differences in urban development patterns. However, a number of recent life-cycle analysis (LCA) studies of alternative vehicle/fuel technologies indicate that the "indirect" emissions that result from supplying the vehicles, the fuels, and the built infrastructures that are also required to provide transportation services are of a similar order of magnitude as the direct emissions, and therefore ought to be incorporated into carbon footprinting studies if policy making is to be fully informed (DeLucci, 2003; ANL, 2009; EPA, 2006; Chester and Horvath, 2008; The Climate Registry, 2008; Green Design Institute, 2009; Natural Resources Canada, 2009). These indirect multipliers are found to vary a good deal across modes of travel, and to affect metropolitan areas differently, depending on the mix of auto and truck vehicle miles of travel.

In this paper recent results from this LCA literature are used to combine these direct and indirect emissions on a per vehicle mileage basis, producing an estimate of the total "upstream" (EPA, 2006) plus direct CO_2 emissions from metropolitan highway travel activity. It is emphasized that these indirect emissions estimates are approximate at this stage. Not only is the state-of-the-art in calculating such indirect emissions in its early stages as far as most transportation modes are concerned, but no two major studies have adopted the same set of activities to measure these emissions, or made the same assumptions regarding energy consumption rates from the individual activities they include in their "cradle-to-grave" LCA methodologies. Using selected values from the recent literature our results are meant to be illustrative of the range of CO_2 emissions likely to be occurring.

The next section of the paper described the study's database and how it was used to compute these direct plus upstream GHG emissions, standardizing them on a) a per capita and b) a per dollar of gross metropolitan product basis. Section 3 presents the key empirical findings. In Section 4 this data is used to carry out a preliminary regression analysis of the relationship between the direct GHG emissions and some common urban form variables. A final section of the paper summarizes the empirical findings.

2. METHODOLOGY

This section describes how the CO_2 emissions were computed for the nation's 100 largest metropolitan areas, for calendar year 2005. These carbon "footprints" are made up of the three components of carbon dioxide emissions from the transportation sector: automotive traffic, truck traffic, and transit vehicle activity. For auto and truck emissions the following four step process was used (see Figure 1) :

1) Data was gathered and processed to produce estimates of the daily vehicle miles of travel (DVMT) within each metro area.
2) These DVMT estimates were then converted to gallons of fuel consumed, broken down by major fuel types: principally gasoline and petro-diesel but also liquefied petroleum gas (LPG) and other small percentage contributors involved in vehicle operations.
3) This fuel consumption was then in turn converted into a) its equivalent energy content, measured in British thermal units (Btu) and b) its equivalent carbon content, to produce an estimate of the carbon footprint created by each metro area's estimated auto and truck vehicular travel activity. Results are multiplied by 44/12 to convert from carbon to carbon dioxide, and by 365 to put these emissions on an annual basis.
4) Finally, the "upstream" carbon dioxide emissions from the life cycles of fuels, infrastructures, and vehicles, were added to these direct emissions, using results from the recent literature to direct + indirect assessment of each metro areas transportation-based CO_2 footprint.

In computing the annual CO_2 emissions from public transit for each metropolitan area a three step process was followed (see Figure 2):

1) Data from the Federal Transit Administration's (FTA) National Transit Database (NTD) (FTA, 2008) on transit agency reported annual fuel consumption was combined with supporting sources to produce estimates of the annual fuel consumed for transit systems operating within each metro area for the year 2005. This fuel data is broken down by the different fuel types: gasoline, diesel, liquefied petroleum gas (LPG), liquid and compressed natural gas (LNG and CNG), kerosene, bio-diesel and electricity.
2) Fuel consumption was then converted into a) its equivalent energy content, measured in British thermal units (Btu) and b) into its equivalent carbon content, to produce a rough estimate of the carbon footprint created by each metro area's public transit vehicle operations. Results are multiplied by 44/12 to convert from carbon to carbon dioxide.
3) Finally, these direct emissions were factored to include upstream emissions associated with the provision of transit vehicles, fuels and their supporting infrastructures.

The following paragraphs provide more detail on the data and computations involved in each of these steps.

2.1 Calculating Automobile and Truck Vehicle Miles of Travel

The calculations of the Vehicle-Miles Traveled (VMTs) for the top 100 metro areas are based on two data sources: 1) the Highway Performance Monitoring System (HPMS) (FHWA, 2008a), and 2) Highway Statistics (FHWA, 2008b). The 2005 version of the HPMS database used in this study, and composed of 119,528 sampled data records, was used to calculate daily VMT

(DVMT) estimates for three types of highway vehicle: passenger vehicles (composed of autos and small trucks, including sports utility vehicles), single unit trucks, and (generally much larger) combination trucks. While these data are reported by FHWA on an urbanized area (UA) basis, the present study re-processed the raw HPMS data records to capture all sampled vehicle counts in those counties making up the study's designated 100 largest metropolitan areas. For the most part these metro areas are larger in geographic extent, and therefore also in driving population, than the UAs reported in Highway Statistics.

FHWA also supplied separate estimates of "local" DVMT traffic for its UAs, for 2005. This is traffic that is not captured by HPMS traffic counters, but which takes place on the many miles of lowest capacity local roads that pass through, for example, many residential areas, and which are effectively "off the network". Manual assignment of each UA to its appropriate metro area was then required. Lacking other data, an assumption had to be made about the percentage of this local DVMT associated with a specific truck type Our default assumption is that 90 percent of the local truck VMT occurs in single unit trucks and the other 10 percent in combination trucks.

2.2 Calculating Automobile and Truck Direct Energy Consumption and Carbon Emissions

Oak Ridge National Laboratory's Transportation Energy Data Book (Davis et al, 2007) and FHWA's Highway Statistics Publication were used to estimate the average fuel efficiency (miles per gallon) for automobiles. For trucks, data from the U.S. Census Bureau's 2002 Vehicle Inventory and Use Survey (VIUS) (Census Bureau, 2004) was combined with this ORNL and FHWA data to calculate the average fuel efficiency for both single unit and combination trucks for each state. The VIUS reports fuel consumption in different truck size classes based on 2 mpg ranges (5-6.9 mpg, 7-8.9 mpg, etc.). Using this data we obtained a nationwide average mpg of roughly 8.6 for single unit trucks and 6.1 for combination trucks. In contrast, the Transportation Data Book (Edition 26, 2007) reports values of 8.8 mpg for single trucks and 5.9 mpg for combination trucks for the year 2005. For single unit trucks the values for average mpg were therefore multiplied by a factor 8.8/8.6. For combination trucks the factor 5.9/6.1 was used. Multiplying the total DVMTs per vehicle class by their respective fuel shares and dividing these values by the state-specific average mpg's in each truck class then gives the number of gallons of fuel consumed by trucks in each metro area.

Using numbers published by the U.S. Environmental Protection Agency (EPA, 2002) and multiplying the total gallons of fuel consumed by each fuel's gross heat content, the total Btus for each metro area were calculated. Multiplying these numbers by each fuel type's carbon coefficient (reported in Figure 1 as Tg/QBtu, or Teragrams per Quadrillion Btu) and summing over all fuel types (i.e. principally gasoline, diesel, and gasohol) gives the direct transportation carbon emissions for each metro area. Carbon dioxide emissions are then calculated by multiplying this carbon by 44/12.

Figure 1: Highway (Automobile, Truck) Methodology

Highway

Step 1: Estimate DVMT Within Each Metro

Data: HPMS, Highway Statistics

On HPMS Network:

$DVMT_{Total,\ section}$ = Section length * AADT * Std. Expansion Factor

$DVMT_{Single\ Unit,\ section} = DVMT_{Total,\ section}$ * % Single Unit Trucks

$DVMT_{Combination,\ section} = DVMT_{Total,\ section}$ * % Combination Trucks

$DVMT_{Car,\ section} = DVMT_{Total,\ section} - (DVMT_{Single\ Unit} + DVMT_{Combination})$

Aggregate sections in each Metro to get $DVMT_{METRO,\ TOTAL}$, $DVMT_{METRO,\ CAR}$, $DVMT_{METRO,\ SINGLE\ UNIT}$, $DVMT_{METRO,\ COMBINATION}$

Off HPMS Network (local) *:*

$DVMT_{local,\ METRO,\ CAR} = (DVMT_{METRO,\ CAR}/DVMT_{METRO,\ TOTAL}) * DVMT_{local,\ URBAN} * (DVMT_{METRO,\ TOTAL}/DVMT_{URBAN})$

$DVMT_{local,\ METRO,\ SINGLE\ UNIT} = ((DVMT_{METRO,\ SINGLE\ UNIT} + DVMT_{METRO,\ COMBINATION})/DVMT_{METRO,\ TOTAL}) * DVMT_{local,\ URBAN} * (DVMT_{METRO,\ TOTAL}/DVMT_{URBAN}) * 0.9$

$DVMT_{local,\ METRO,\ COMBINATION} = ((DVMT_{METRO,\ SINGLE\ UNIT} + DVMT_{METRO,\ COMBINATION})/DVMT_{METRO,\ TOTAL}) * DVMT_{local,\ URBAN} * (DVMT_{METRO,\ TOTAL}/DVMT_{URBAN}) * (1 - 0.9)$

Step 2: Convert to Fuel Consumption (in gallons)

Data: Transportation Energy Data Book, Highway Statistics , VIUS

Cars*:*

Fuel Shares:

Gasoline	*0.669*
Gasohol	*0.326*
Diesel	*0.005*

Average Mileage 2005*: 19.7 miles per gallon*

Trucks*:*

Fuel Shares: *Share of Fuel Type X = Reported Truck Miles Using Fuel Type X / Total Reported Truck Miles*

Average Mileage (VIUS, 2002): *Avg MPG Fuel Type X = ((Miles 'mpg class 1'/Total miles fuel type X)* Middle value 'mpg class 1') + ((Miles 'mpg class 2'/Total miles fuel type X)* Middle value 'mpg class 2') + … etc.*

Adjustment factors for 2005: *8.8/8.6 for Single Unit and 5.9/6.1 for Combination*

Step 3: Convert to BTU and Carbon Emissions

Heat Content and Carbon Coefficients*:*

FUEL:	*Gasoline*	*Diesel*	*Gasohol*	*LPG/Propane*
Heat Content (Btu/gal)	*125,000*	*138,700*	*120,900*	*91,300*
Carbon Coeff (Tg/Qbtu)	*19.34*	*19.95*	*19.34*	*16.99*

Step 4: Conversion from direct emissions to total emissions (including upstream)

Data: For Cars: Chester and Horvath (2008), for trucks: EPA *and* Chester and Horvath (2008)

*Total Emission = Direct Emissions * Multiplication Factor*

Multiplication factors: 1.56 for Auto, 1.43 for Single Unit Trucks, 1.38 for Combination Trucks

Figure 2: Public Transit Methodology

Transit

Step 1: Calculate Fuel Consumption (in gallons or MWh)

Data: National Transit Database (NTD)

<u>Agencies that reported fuel consumption:</u>

NTD Table 17 (by agency by mode by fuel type)

Aggregated over all agencies within a particular metro area.

<u>Agencies that did not report fuel consumption, but only VMT:</u>

Calculate average fuel efficiency and the fuel shares from NTD Table 17, then calculate 'missing' fuel consumption from reported VMT from NTD Table 19:

$$\text{Avg. MPG}_{\text{mode X}} = \text{SUM(reported fuel mode X)/SUM(reported corresponding miles mode X)}$$

Fuel consumption for 'missing' agency Y:

$$\text{Total fuel consumption}_{\text{agency Y, mode X}} = \text{Reported miles}_{\text{agency Y, mode X}} / \text{Avg. MPG}_{\text{mode X}}$$

Fuel by different fuel type:

$$\text{Share fuel Z}_{\text{mode X}} = \text{SUM (reported consumed fuel Z)/SUM(reported consumed fuel total)}$$

Then:

$$\text{Fuel Y consumption}_{\text{agency Y, mode X}} = \text{Total fuel consumption}_{\text{agency Y, mode X}} * \text{Share fuel Y}_{\text{mode X}}$$

Step 2: Convert to BTU and Carbon Emissions

<u>Heat Content and Carbon Coefficients (applied to non-electricity modes):</u>

FUEL:	*Diesel*	*Gasoline*	*LPG*	*LNG*	*Methanol*	*Ethanol*	*CNG*	*Kerosene*	*Bio-Diesel*	*Other*
Heat Content (Btu/gal)	138,700	125,000	91,300	90,800	64,600	84,600	84,700	135,000	126,206	104,545
Carbon Coeff (Tg/Qbtu)	19.95	19.34	16.99	14.47	17.39	20.80	14.47	19.72	20.45	18.18

Step 3: Convert from direct emissions to total emissions (including upstream)

Data: Chester and Horvath (2008)

*Total Emission = Direct Emissions * Multiplication Factor*

Multiplication factors: 1.4 for Bus

2.3 Calculating Public Transit VMT, Direct Energy Consumption and Carbon Emissions

Motor fuel consumption as well as electricity consumption data is reported directly by public agencies to the Federal Transit Administration's National Transit Database (NTD). The present study re-processed the 2005 NTD data records to capture fuel consumed by agencies operating within the urbanized areas (UAs) making up the study's designated 100 largest metropolitan areas based on a cross-walk compiled by the authors. Table 17 of the NTD reports fuel consumption by agency and by fuel type for 13 different transit modal services, including fixed route bus, heavy and light rail services, vanpools and jitney services, and ferries. Where an agency failed to report this information for 2005, but did report annual vehicle miles (in Table 19 of the 2005 NTD), an average mpg per revenue vehicle mile operated figure was assigned based on taking the average fuel efficiency for those agencies that did report (see Southworth, Sonnenberg and Brown, 2008 for details).

2.4 Calculating "Upstream" Life Cycle CO_2 Emissions

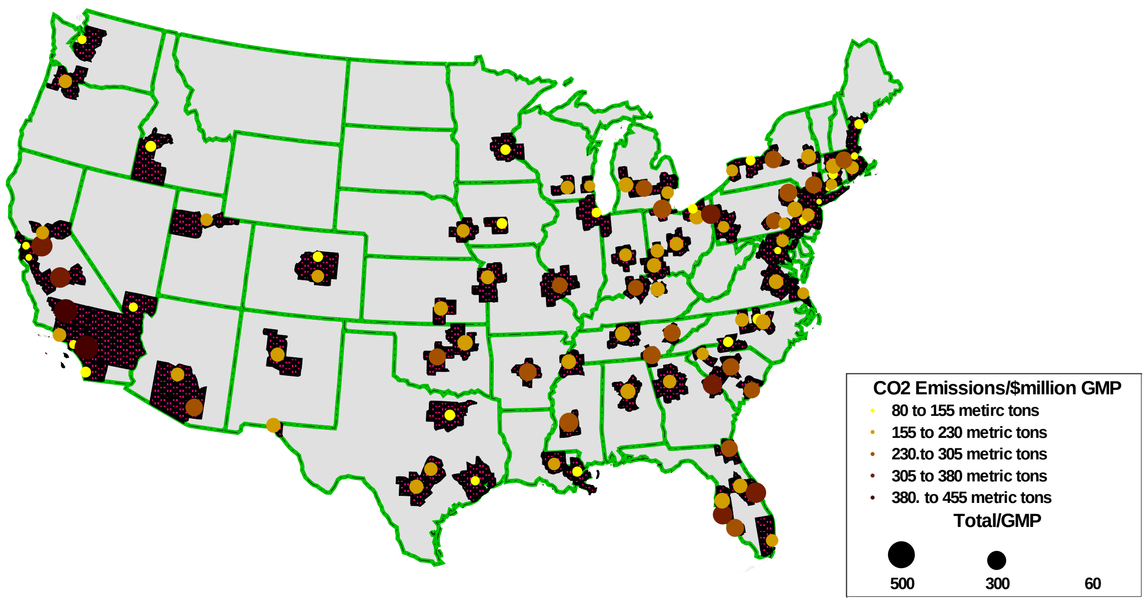
For automobile and transit activity the life-cycle assessment results reported by Chester and Horvath (2008) are used to factor up the direct vehicle activity based emissions to a more complete representation of the life-cycle CO_2 emissions associated with each transportation mode. Their method quantifies energy inputs and emissions associated with the entire life cycle of the fuels, vehicles, and also many of the built infrastructures (roadways, tracks, terminals, depots, parking structures, offices, etc) and other support activities (notably insurance) required to support these vehicle movements. They accomplish this using a combination of the two most common forms of LCA: a highly detailed process model that quantifies each of the resource inputs and environmental outputs at each stage in the vehicle, fuel, or infrastructure production process, and an economic input-output analysis that integrates traditional I/O modeling with environmental databases to produce an inventory analysis of the entire supply chain associated with a product or service (see Hendrickson et al, 1998; Green Design Institute, 2009). They conclude that "Current results show that total energy and greenhouse gas emissions increase by as much as 1.6X for automobiles, 1.4X for buses,…."

Looking further into the report by Chester and Horvath, and using national vehicle fleet shares (Davis et al, 2008) to re-weight their sedan, SUV and Pick-Up results, we use an average passenger vehicle ("auto") total/direct emissions multiplier of 1.56 in the present study. Similarly, for buses we use an average multiplier, taken across all fuel types (principally diesel) of 1.40, which value also falls in the middle of the range suggested by EPA (2006). For trucks we used the upstream emissions factors reported by the U.S. Environmental Protection Agency (EPA, 2006) who present a range of values that in turn make use of the results reported in the LEM (DeLucchi, 2003) and GREET (ANL, 2009) LCA models. However, these emissions include only the vehicle and fuel life-cycle emissions. Based on Chester and Horvath we estimate that emissions from built infrastructure accounted for 3% of the upstream emissions for buses and we adopt this same percentage for trucks. We selected multiplication factors of 1.43 for light duty trucks and 1.38 for heavy-duty (combination) trucks, which again puts us in the middle of the range of figures presented by EPA(2006). "Downstream" emissions, including the emissions resulting from any form of materials re-cycling or salvage operations are not included in any of these numbers. They are expected to be quite small at present compared to the rest of each mode's LCA emissions.

3. EMPIRICAL FINDINGS

The most significant general finding to come out of the above data analysis is that large differences in carbon dioxide footprints exist across the nation's largest 100 metropolitan areas, when measured on either a per capita (i.e. per resident) or per dollar of Gross Metropolitan Product ($GMP) basis. (Note that this GMP measure is a relatively new one in economic analysis, and represents the metropolitan area equivalent of the nation's Gross Domestic Product, or GDP). When looked at across all 100 metro areas these results produce a highest/lowest emitter ratio of 2.49 (12.19/4.90) on a per capita basis, and an even greater highest/lowest emitter ratio of 4.82 (409.7/85.0) on a per $ million GMP basis. Figure 3 maps these per GMP emissions.

Figure 3. Map of Metric Tons of CO_2 Emissions per $ Million GMP in 2005



Figures 4 and 5 graph these per capita and per $GMP statistics respectively, ranked from highest to lowest across all of the 100 metro area, and broken down by vehicle types. Tables 1 and 2 list the 10 highest and lowest emitting metro areas on a per capita (Table 1) and per $ million GMP (Table 2) basis. The Top 10 emitters on both measures favor smaller MSAs and/or areas with higher than average contributions from truck VMT to their carbon totals. In contrast, among the lowest emitters on both measures are some of the nation's oldest, largest and most densely populated cites: Boston, Los Angeles, New York, Philadelphia, San Francisco and Washington DC. At 4.90 metric tons of CO_2 per person the New York – Northern New Jersey metro area, with its much higher share of public transit riders, comes in as the lowest emitter; while Bakersfield, CA, which has the highest combination truck VMT share and one of the larger overall truck shares, comes in as the highest emitter at 12.19 metric tons per capita. Bridgeport,

CT is the low emitter on a per $GMP basis, at 85.0 metric tons per $ million of GMP, while Riverside, CA is the high emitter at 409.7 metric tons per $million of GMP.
Note that the above estimates are based on sample-expanded VMT counts within each metro area, which includes the VMT from only that portion of the many trips which pass through an area. This includes many relatively low mpg combination truck trips, which typically pass through urbanized areas along Interstate routes. This is significant because this combination truck share varies a great deal across the 100 metro areas, from a low of 2.1% (Honolulu, HI) to a high of 26.0% (Bakersfield, CA), for an average metro area carbon contribution of 12.5%. Bakersfield, CA, Toledo, OH, Lexington, KY, Little Rock, AR, Indianapolis, IN and Harrisburg, PA top the list of high combination truck shares. Similarly, total truck shares vary a good deal, from a low of 6.3% in Honolulu, HI to a high of 37.3% for Toledo, OH. For example, Bakersfield and Toledo both appear among the top ten metro area emitters per capita and per $GMP, while Honolulu appears among the lowest ten. This, among other data quality issues (and footprint concept issues), notably the method of designating the metropolitan area boundaries used by the Census Bureau, should be borne in mind when comparing results across different metro areas.

Public transit's contribution to highway travel-based carbon dioxide emissions was just under 0.5% when averaged over all 100 metros for 2005. And here the public transit operations in the New York-Northern New Jersey-Long Island metro dominate the national results, accounting for over 19% of the transit carbon dioxide emitted by all 100 metro areas in 2005 (not including rail

Figure 4. 2005 CO_2 Emissions by Metropolitan Area: Metric Tons/Capita

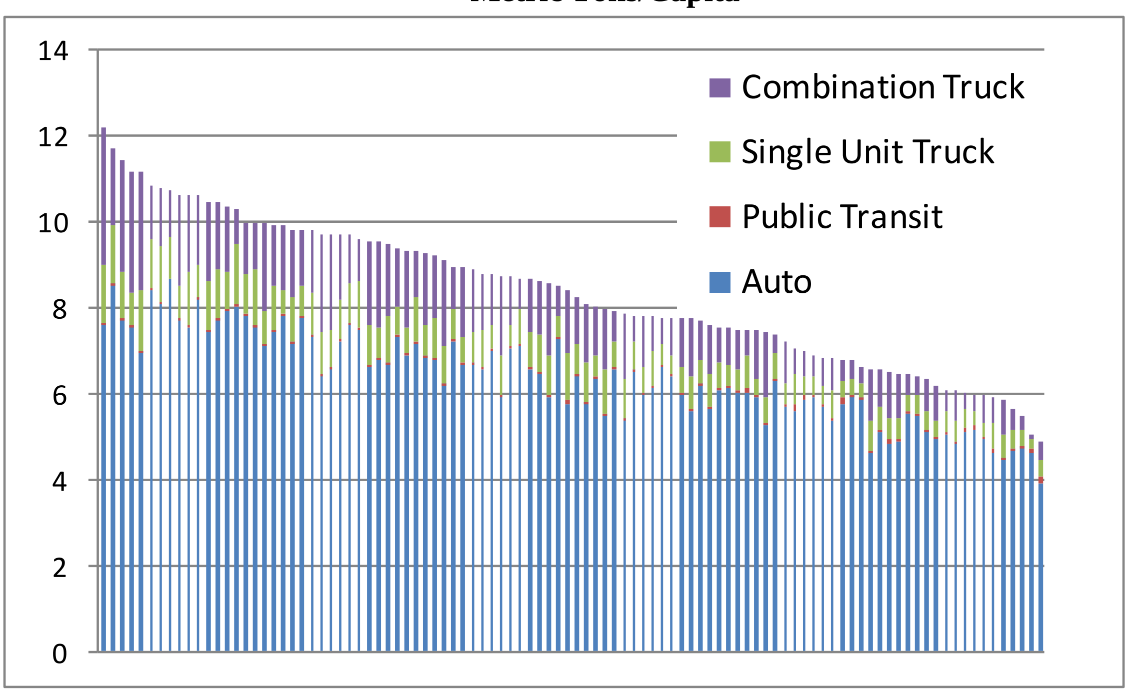


Figure 5. 2005 CO_2 Emissions by Metropolitan Area: Metric Tons/$million Gross Metropolitan Product

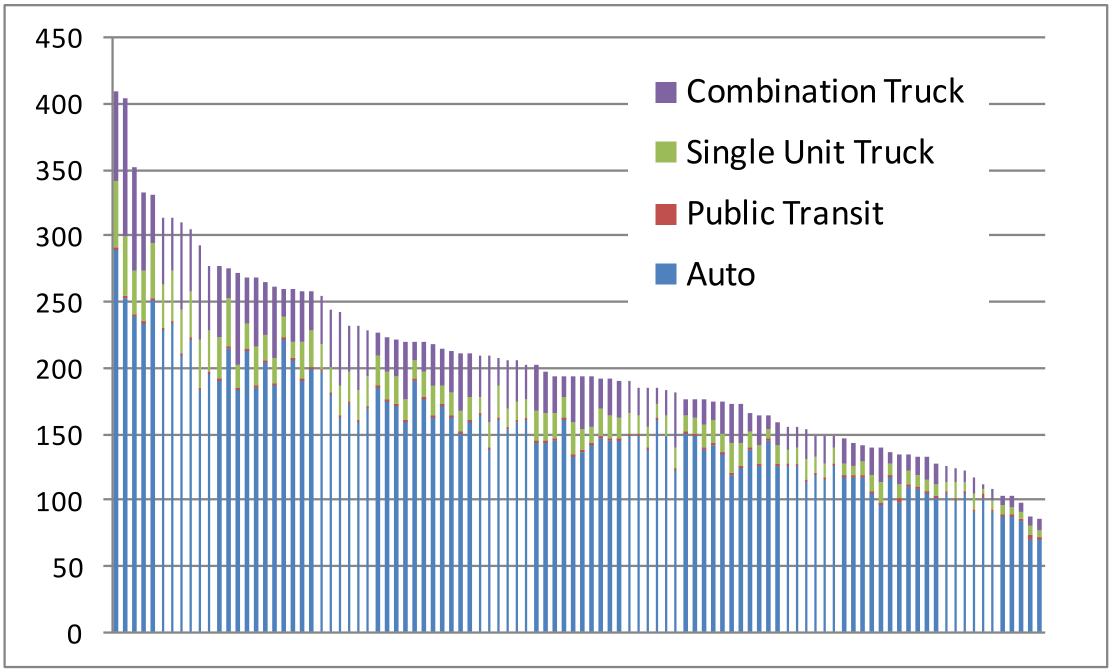


Table 1. CO_2 per Capita in 2005: 10 Highest and Lowest Metro Area Emitters

METRO	Auto	Public Transit	Single Unit Truck	Combination Truck	Total
1 Bakersfield, CA	7.65	0.02	1.36	3.17	12.19
2 Jackson, MS	8.56	0.01	1.35	1.80	11.73
3 Harrisburg, PA	7.74	0.02	1.11	2.58	11.45
4 Little Rock, AR	7.58	0.02	0.74	2.86	11.20
5 Toledo, OH	6.98	0.03	1.42	2.75	11.18
6 Jacksonville, FL	8.42	0.04	1.16	1.24	10.86
7 Sarasota, FL	8.10	0.02	1.32	1.34	10.78
8 Trenton, NJ	8.70	0.00	0.94	1.08	10.73
9 Nashville, TN	7.74	0.01	0.78	2.12	10.65
10 Riverside, CA	7.56	0.02	1.28	1.78	10.64
……………					
91 Boise City, ID	4.87	0.01	0.48	0.70	6.05
92 Boston, MA	5.11	0.12	0.40	0.40	6.04
93 Los Angeles, CA	5.18	0.06	0.34	0.38	5.96
94 Las Vegas	4.96	0.04	0.33	0.62	5.95
95 Philadelphia, PA	4.63	0.11	0.59	0.61	5.94
96 Lancaster, PA	4.50	0.02	0.54	0.81	5.87
97 Buffalo, NY	4.70	0.04	0.44	0.50	5.66
98 Rochester, NY	4.76	0.03	0.36	0.35	5.50
99 Honolulu, HI	4.61	0.11	0.21	0.11	5.04
100 New York, NY-NJ	3.90	0.18	0.39	0.43	4.90

Table 2. CO_2 per $Million of GMP in 2005: 10 Highest and Lowest Metro Area Emitters

	METRO	Auto	Public Transit	Single Unit Truck	Combination Truck	Total
1	Riverside, CA	291.23	0.69	49.27	68.49	409.68
2	Bakersfield, CA	253.51	0.52	45.23	104.95	404.22
3	Stockton, CA	239.38	1.13	34.04	76.92	351.47
4	Fresno, CA	235.46	0.80	37.60	59.51	333.37
5	Palm Bay, FL	251.58	0.46	43.01	36.26	331.31
6	Augusta, GA	229.64	0.15	33.01	51.26	314.05
7	Sarasota, FL	235.45	0.60	38.33	38.90	313.29
8	Youngstown, OH-PA	210.77	0.37	33.64	65.02	309.80
9	Jackson, MS	222.64	0.24	35.08	46.92	304.88
10	Toledo, OH	183.41	0.76	37.41	72.26	293.84
	…………….					
91	Seattle, WA	98.61	3.01	12.06	10.23	123.92
92	Los Angeles, CA	105.88	1.27	6.92	7.75	121.82
93	Philadelphia, PA	91.07	2.10	11.67	11.99	116.82
94	Honolulu, HI	101.49	2.47	4.62	2.32	110.91
95	San Francisco, CA	90.74	1.84	6.64	9.04	108.26
96	Boston, MA	87.15	2.06	6.87	6.81	102.88
97	Washington, DC	87.20	2.22	5.60	7.83	102.86
98	San Jose, CA	84.54	0.70	6.29	6.52	98.05
99	New York, NY-NJ	69.38	3.24	7.03	7.69	87.34
100	Bridgeport, CT	70.69	0.31	5.37	8.61	84.99

transit emissions). As a result, the public transit operations in the New York metro area analyzed in this study are estimated to have contributed almost 2% of that area's total carbon dioxide emissions in 2005. Highway (mainly bus, but also vanpool and some ferry trips) also contributed over 2.4% of the total emissions in Seattle WA, and over 2.2% in Honolulu, HI. Transit emissions were also more than 1% of Boston MA, Chicago IL, San Francisco CA and Washington DC total emissions in 2005, and just below 1% in Philadelphia and Los Angeles.

4. REASONS FOR THE VARIABILITY IN CO_2 EMISSIONS ACROSS METRO AREAS

Such results naturally lead the analyst to wonder what causes such large differences in emissions rates across metro areas: and most importantly, how much of this variation can be impacted by suitable CO_2 emissions reduction policies. In particular, what contributions to such differences come from differences in vehicle mix (notably a large truck VMT component), versus differences in urban development patterns.

The following analysis was based on the hypothesis that differences in carbon emissions across metro areas are a function of differences in average fuel efficiency occasioned by differences in a metro area's vehicle mix, i.e., in its percent auto, single unit truck, combination truck, and transit VMTs; and by differences in the size and structure of each metro area, and in particular in the extent to which some metros are more compact than others. To capture this latter effect, a number of urban form variables were developed for 97 of the 100 metro areas (one or more data gaps meant that the metropolitan areas of Bridgeport CT, Honolulu HI, and Palm Bay FL could not be included in the analysis). As noted by Ewing et al (2002), who carried out a correlation analysis on aggregate metropolitan area-level data in their study of urban sprawl, such studies cannot definitively establish cause-and-effect relationships. But where statistically significant relationships are found to exist between variables this establishes at least a necessary condition for causality, and one warranting further investigation. Even so, the size and direction of such statistical relationships must be put into proper context. One way to do this is to control for other "confounding" variables, including variables that may prevent a wrong diagnosis between a supposedly "dependent" and "explanatory" variable in some cases. The following statistical analysis therefore represents only an initial excursion into the potential quantitative impacts of urban form factors on carbon emissions from highway travel. The analysis is also carried out using only the *direct* emissions, either on a per capita or on a per $million GMP, as the dependent variable, i.e. using that portion of the LCA emissions capable of being directly affected by household and business travel practices and by the physical pattern of urban development.

Based on the past literature linking travel, energy consumption and urban form, sixteen different urban form measures, dealing with population, employment and housing dispersion and density and with jobs-housing balances, were developed. The reader is directed to Southworth et al (2008) for details.

Vehicle Mix Variables: As expected, strong positive correlations were obtained between trucking's share of metro area VMT and both CO_2 emissions per capita and per $million GMP, while, also as expected, negative correlations were obtained between public transit's share of metro area VMT and both emissions measures. Given the small contribution of transit VMT to metro emissions, however, this variable may be having most of its impact as a surrogate for other urban form variables, including metro area size as well as population and job density.

Urban Form Variables: Negative correlations between emissions and both population (DENP) and employment (DENJ) density variables were found, measured here as number of persons and number employees per acre of developed land respectively. Similarly, a number of population and employment centrality, spatial concentration, and job-housing balance indices were experimented with. Of these, the variable CONCPD, a spatial population dissimilarity index (delta) based on zip code areas, proved the most successful when used within multivariate regressions. CONCPD measures the extent to which residents are evenly distributed across the metro area. It ranges in value from 0 to 1, with lower scores representing more concentration of persons or jobs across the metro, and was computed as (see Galster et al., 2001):

$$CONCPD = 1/2\Sigma\ ABS[(p/P)-(a/A)]$$

where:
p = the population of the kth zip code area
P = the total population of the metro area
a = the area of the kth zip
A = the total area of the metro area
ABS is syntax for absolute value

Socio-Economic Variables: A single socio-economic variable found its way into the best fitting regression models, dollars of gross metropolitan product per capita (GMP/capita), which we take here to be a surrogate for metro area wealth, and which is measured in $1,000's of dollars in the regression equations presented below.

Metropolitan Area Size Variables: Tables 1 and 2 show that many of the nation's largest metropolitan areas are among those with lower emission on a per capita and per GMP basis. Emissions per capita are highly (negatively) correlated with the size of a metro area, measured either by its number of residents ($R = -0.39$) or by its $ of GMP ($R = -0.42$) in 2005. Emissions per $GMP show similar correlations: $R=-0.40$ with population size, and $R= -0.48$ with total $GMP. Efforts to introduce these and other variables into the regressions below failed due to correlations between these and other variables: notably with transit share, density measures, and GMP/capita.

Applying ordinary least squares (OLS) regression to the above variables produced the results shown in Table 3. LN(DENJ) here refers to the natural log of the employment density variable. As expected, both this density measure and the CONCPD measure of spatial concentration of population activity are negatively correlated with carbon dioxide emissions, suggesting benefits to be gained from more compact urban development. Figure 6 shows the relationship between DENJ (jobs per developed acre) and truck only emissions per $million GMP: a relationship reminiscent of the relationship between population density and passenger vehicle miles of travel often referenced in the urban form/urban sprawl literature (Ewing and Cervero, 2001; TRB, 2009). Additional efforts to develop separate regressions for truck versus passenger 9auto + bus) travel await further work.

5. SUMMARY

Four significant empirical findings come out of the research presented in this paper. First, there is considerable variability in the carbon dioxide emissions from highway travel on both a per capita and per dollar of gross metropolitan product basis when looked at across the nation's top 100 metropolitan areas. Second, and as would be expected, the amount of low mpg trucking activity within a metro area plays a major role in this variability. Third, and recognizing that current data sources are based on an (albeit large) sample of traffic counts, some of this variability can also be linked to a metro area's average employment density as well as the way its population is concentrated within its boundaries. Finally, and again as might be expected, more prosperous metros, on a per capita basis, also have higher carbon dioxide emissions than less prosperous ones.

Table 3. Regression Results

Dependent variable = Metric Tons CO_2 per Capita in 2005:

Regression Statistics	
Multiple R	0.787
R Square	0.619
Adjusted R Square	0.598
Standard Error	0.695
Observations	97

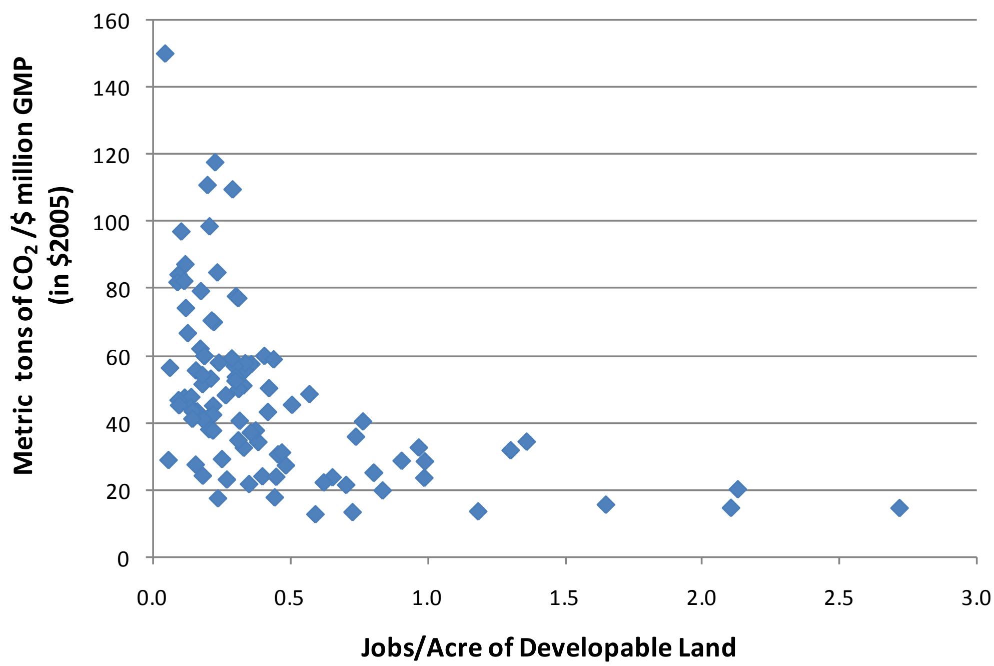
	Coefficients	*Standard Error*	*t Stat*	*P-value*
Intercept	2.888	0.587	4.920	0.000
Truck VMT Share	0.209	0.028	7.366	0.000
Transit VMT Share	-0.558	0.133	-4.204	0.000
CONCPD	-1.494	0.625	-2.390	0.019
LN(DENJ)	-0.242	0.122	-1.984	0.050
GMP/Capita (000s)	0.032	0.009	3.687	0.000

Dependent Variable = Metric Tons CO_2 per \$ million of GMP in 2005:

Regression Statistics	
Multiple R	0.880
R Square	0.774
Adjusted R Square	0.762
Standard Error	20.620
Observations	97

	Coefficients	*Standard Error*	*t Stat*	*P-value*
Intercept	182.641	17.419	10.485	0.000
Truck VMT Share	5.953	0.841	7.077	0.000
Transit VMT Share	-7.265	3.937	-1.845	0.068
CONCPD	-28.651	18.543	-1.545	0.126
LN(DENJ)	-6.176	3.621	-1.706	0.091
GMP/Capita (000s)	-2.192	0.260	-8.428	0.000

Figure 6. Employment Density vs. CO_2 /$GMP For Truck Travel in 2005



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