DoMobility-Based Performance Measures Reflect Emissions Trends?

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Abstract

Given the commonly assumed association between traffic congestion and emissions, this paper addresses the question of whether mobility-based performance measures are associated with emissions performance measures. We address two facets of the roadway congestion-emissions relationship by investigating: (a) whether congestion performance measures are good indicators of trends in roadway emissions and (b) what transportation performance measures are better suited to portray macroscopic trends in emissions. In order to answer these research questions we estimate macroscopic transportation and emissions performance measures at metropolitan and corridor levels. Comparing several measures, we calculate the correlation between transportation performance measures and emissions. We also present an analytical framework to understand emissions trends as a function of mobility and travel demand variables. Results show that Vehicle Miles Traveled (VMT) and Vehicle Hours Traveled (VHT) are key factors to understanding emissions trends. Mobility measures (such as travel speed and delay) and related congestion measures (such as percent of travel in congestion) are only weakly correlated with emissions.

Keywords: performance measures, congestion, emissions, travel demand

1 Introduction

Motorized transportation's role in decreasing urban air quality and increasing atmospheric greenhouse gases through motor vehicle emissions is a global concern[1], [2]. At the same time, roadway congestion continues to increase in urban areas throughout the world, with varying economic, social, and environmental costs[3], [4]. Increased fuel consumption and elevated emissions from motor vehicles are often tied to roadway congestion because, in general, vehicle efficiency decreases as congestion increases.

As an example, the well-known Urban Mobility Report (UMR) tracks congestion trends in the U.Sand also estimates the amount of fuel "wasted" in congestion [5]; according to the UMR,fuel wastedper vehicle is higher in more congested areas. Public health studies have linked premature mortality to exposure to air pollution from "traffic congestion"[6]. The linkage of congestion and emissions is also suggested by government programs such as the Congestion Mitigation and Air Quality (CMAQ) Improvement Program.The CMAQ program has provided over $14 billion in funding since 1991 for transportation projects with the dual objectives of improved air quality and reducedcongestion[7].

Given the common association of traffic congestion and emissions, this paper addresses the question of whether mobility-based performance measures are associated with emissions performance measures. We focus on the macroscopic relationships between transportation performance measures and emissions to ask and answer the following research questions: Do mobility trends reflect emissions trends? If not, what congestion or transportation performance measures can be used to better understand and indicate emissions trends?

In order to address these research questions we estimate aggregated emissions and transportation performance measures at the metropolitan and corridor levels. Comparing different measures, we statistically assess the correlation between transportation measures and emissions. We also provide an analytical framework to assess the relationship between key traffic and emissions variables. The next section presents a literature review.

2 Literature Review

Transportation performance measures have been widely studied in the last two decades and congestion performance measures are an area of active research[8–10]. Most congestion performance measuresaddress mobility or its impedance[11]. Mobility-oriented performance measures often compare a congested speed or travel time with some threshold for uncongested conditions. Some well-known mobility measures include the Travel Time Index (TTI), the Buffer Time Index (BTI), and the Planning Time Index (PTI) – see [11] for more details. These mobility measures are normalized to the volume of travel (i.e. only sensitive to changes in speeds).

The TTI, in particular, enjoys extensive use in the Urban Mobility Report and elsewhere [12]. The TTI is calculated as the ratio of average peak-period travel time to the travel time on the same facilities in free-flow conditions,

$$TTI = \frac{t}{t_o} = \frac{v_o}{v}, \tag{1}$$

where t and v are the average peak-period travel rate and travel speed, respectively, and t_o and v_o are the off-peak (free-flow) travel rate and travel speed, respectively. Travel rate here is in units of time per distance. In later analysis we use the TTI as a reference mobility measure due to its extensive usage and mass media coverage as a key indicator of the performance of the U.S. transportation system; see for example[13], [14]. One of the most appealing characteristics of the TTI is its simplicity and intuitiveness that allow a mass media discussion of congestion trends, analysis, and comparisons among major USA cities.

Although widely known and published, the use of the TTI as a key performance measure has also been criticized. Cortright [15]criticizes the approach of the UMR because this report uses a normalized travel time measure for its primary congestion indicator (the TTI). Cortright describes the TTI as an unrealistic measure that neglects the roles of travel distances, land use, and accessibility. He states a need for new macroscopic congestion measures and offers as alternatives estimates of excess travel distance and excess travel time. Also, European policy makers have indicated that speed-based performance measures fail to represent the full multi-dimensionality of urban traffic congestion [3].

Previous research has addressed the impacts of congestion on emissions directly – e.g.[16–18]. It is well established that very low travel speeds or stop and go traffic conditions lead to higher emissions on a per-vehicle per-mile traveled basis.Recently there have been attempts to link traffic performance and emissions to produce environmental transportation performance measures leveraging on existing freeway data archives[19], [20]. For commercial vehicle freight movements, a recent research effort linked mobility, economic, and emissions performance measures[21]. However, to the best of the authors' knowledge there is no previous research effort focusing on the widely tracked and reported traffic congestionmeasures and their relationship with roadway emissions.

3 Methodology

In this research we estimate aggregate emissions and traffic/congestion performance measures at the metropolitan and corridor levels. We then compare these measures to look for statistical associations. We also present an analytical framework that helps describe the relationships between key traffic and emissions variables.

3.1 MetropolitanEmissionsand Performance Measures

The metropolitan analysis addresses annual-average peak-period emissions and congestion performance of 101 U.S. urban areas described in the UMR for 2010 [5]. We focus the analysis on greenhouse gas emissions, providing results in terms of CO_2e (carbon dioxide equivalent) emissions. Correlation results are also presented for CO (carbon monoxide), $PM_{2.5}$ (particulate matter smaller than 2.5 microns), NO_x (nitrogen oxides), and HC (gaseous hydrocarbons) emissions. The UMR provides estimates of the annual average peak-period speeds on freeways and arterials for 101 U.S. urban areas in 2010. This analysis follows the UMR methodology and assumptions including free-flow speeds of 60 and 35 mph, respectively, for freeways and arterials.

We calculate average peak-period vehicle emissions rates $e(v)$ as a function of average travel speed for each facility type and urban area combination. For emission rates estimates we draw from previous research on the congestion-emissions relationship[16]. This research estimated fleet-wide emissions-speed curves using the function

$$e(v) = \exp\left(\sum_{i=0}^{4}\left(a_i \cdot v^i\right)\right) , \tag{2}$$

where $e(v)$ is the average emissions rate (in grams/vehicle-mile) at average travel speed v (in miles per hour), with parameter estimates a_i. We use fitted parameters a_i as shown in Table 1for freeways and arterials – drawn from separate previous research[22]. These coefficients are based on the full 2010 Portland, Oregon on-road vehicle fleet and the EPA's MOVES mobile-source emissions model. The coefficients of Table 1provided a very good fit ($R^2 > 0.96$) for emissions rates using average travel speed as the independent variable [22].

As a comparison, we also estimated CO_2 emissions using a_i parameters from research by Barth and Boriboonsomsin utilizing a California vehicle fleet[16]. Although the absolute values of total emissions varied, the trends and relationships with other variables were essentially the same as those found using the coefficients from Table 1. Results based on the Barth $a_i$parameters are thus excluded from this paper for brevity.

Table 1. Emissions-Speed Curve Fit Parameters

	Freeways				
	CO_2e	**CO**	**$PM_{2.5}$**	**NO_x**	**HC**
a_0	8.191	2.885	-1.223	1.897	0.3352
a_1	-0.1826	-0.1788	-0.1769	-0.1656	-0.2040
a_2	0.006339	0.006629	0.006640	0.005830	0.006643
a_3	-9.690E-05	-1.092E-04	-1.127E-04	-8.928E-05	-1.012E-04
a_4	5.357E-07	6.518E-07	6.724E-07	4.936E-07	5.674E-07

	Arterials				
	CO_2e	**CO**	**$PM_{2.5}$**	**NO_x**	**HC**
a_0	8.161	2.772	-1.277	1.852	0.2974
a_1	-0.1735	-0.1378	-0.1618	-0.1554	-0.1960
a_2	0.005899	0.004602	0.005876	0.005390	0.006389
a_3	-8.937E-05	-7.356E-05	-9.883E-05	-8.239E-05	-9.841E-05
a_4	4.929E-07	4.435E-07	5.896E-07	4.572E-07	5.576E-07

We estimate total peak period emissions for each urban area for each year as the summed product of $e(v)$ and total peak period VMT on each facility. Peak-period VMT is estimated as half of the facility's daily VMT, as per the UMR methodology. Daily peak-period emissions per peak-period traveler are calculated for each urban area using the number of peak period travelers (by any mode) in the UMR data tables (derived from the National Household Travel Survey).

The TTI for each urban area is provided in the UMR data tables. Other roadway performance measures for the peak period considered in this study are:

- Peak period VMT and VMT per peak period traveler
- Peak period vehicle hours traveled (VHT) and VHT per peak period traveler
- Peak period delay and delay per peak period traveler
- Roadway congestion index (RCI) –a measure of both the intensity and duration of congestion
- Commuter stress index (CSI) – similar to the TTI but for peak-direction travel only
- Percent of system congested (by lane-miles and VMT)
- Rush hours per day

Of these performance measures, only VHT is not readily available from the UMR data tables (see the UMR documentation for details [5]). Using Equation 1 we can calculate v from the TTI and assumed values of freeway and arterial free-flow speeds. We then divide peak-period VMT by v (by facility) to calculate peak-period VHT.

We also estimate metropolitan emissions and roadway performance trends over time for the 101 U.S. urban areas in the UMR. These calculations are largely the same as for the 2010 estimates. The exception is that peak period speeds by facility are not included in the UMR for previous years, so average speeds by facility are calculated from the TTI using Equation 1 (and assuming the TTI is the same on each facility). Additionally, emissions rate parametersa_i are fixed at the 2010 values shown in Table 1. In this way we are not assessing the impacts of an evolving vehicle fleet, only the impacts of changing traffic conditions and travel volumes. This is considered appropriate for this study in which we are only looking at relationships between emissions traffic variables, not estimating absolute mass emissions. This point is further analyzed and discussed in Sections 3.3 and 7.

3.2 Corridor Emissions and Performance Measures

In order to compare the metropolitan performance measure relationships with relationships at a more microscopic scale, we also perform a corridor analysis on an urban freeway. The corridor under study is I-5 northbound through Portland, Oregon. We look at a 14-mile stretch of roadway using traffic data collected from inductive dual-loop detectors in each lane at longitudinal spacings of just under a mile (there are 16 loop detector stations along the corridor).

Hourly aggregated traffic data are mined from the PORTAL (Portland Oregon Regional Transportation Archive Listing) transportation data archive at Portland State University – available at http://portal2.its.pdx.edu. The northbound freeway is mostly 3 lanes wide through the corridor with a 55mph speed limit and recurrent peak-period congestion.

Traffic data collectedbetween 6am and 10pm were retrieved for the three-year period 2008 to 2010, and analyzed at hourly, daily and monthly aggregations. Time periods with missing data were removed. VMT and VHT were calculated from the measured volumes and speeds at each detector station. Delay was then calculated from VHT and VMT using a free-flow speed of $t_o = 60$mph (which was observed to be the approximate off-peak mean travel speed).

The TTI was calculated using Equation 1 with the same assumed free-flow speed (60mph).The 95th percentile travel time on the corridor, t_{95}, was calculated for each month using hourly average travel times during weekday peak periods. Then $t_{95}$was used to calculate the Planning Time Index, PTI $= t_{95}/t_o$, and the Buffer Time Index, BTI $= (t_{95} - t)/t$. Only weekday peak period data were used to calculate the TTI, PTI, and BTI. The PTI and BTI were only calculated at the monthly aggregation, and the TTI only at the daily and monthly aggregations. Emissions were calculated using Equation 2 and the parameters in Table 1 with hourly mean speeds measured at each detector station.

3.3 Analytical Framework

In this section we present a compact and intuitive analytical framework to understand which macroscopic roadway performance measures reflect the direction of emission trends. Emissions, E (in emissions mass per unit of time, per unit of roadway length), from vehicles passing through a corridor are simply the product of the spatial marginal emissions rate e (emissions mass per vehicle per unit length of roadway traveled), and the traffic volume flow rate q (in number of vehicles per unit of time) measured at a single location:

$$\mathrm{E} = e \cdot q\,.$$

Let us assume that$l$ is the average length of those trips (on the facility, corridor, or area of interest). Then total emissions perunit of time are equal to:

$$T = E \cdot l = e \cdot q \cdot l\ .$$

Emissions elasticities are helpful to understand *changes* in emission trends. The elasticity, ε_e^v, of emissions rate, e, to speed, v, can be expressed as:

$$\varepsilon_e^v = \frac{v}{e} \cdot \frac{\partial e}{\partial v}.$$

The elasticity of travel demand volume q to speed, v, can be expressed as:

$$\eta_q^v = \frac{v}{q} \cdot \frac{\partial q}{\partial v}.$$

Replacing the last two expressions, the partial derivative of emissions with respect to speed is equal to:

$$\frac{\partial E}{\partial v} = \frac{\partial q}{\partial v} \cdot e + q \cdot \frac{\partial e}{\partial v} = \frac{E}{v}\left(\eta_q^v + \varepsilon_e^v\right).$$

Then, per unit of roadway length and per unit of time, emissions elasticity to speed is equal to:

$$\varepsilon_E^v = \frac{v}{E} \cdot \frac{\partial E}{\partial v} = \frac{v}{q \cdot e} \cdot \frac{\partial E}{\partial v} = \eta_q^v + \varepsilon_e^v$$

Similarly, the elasticity of total emissions, $T = E \cdot l$, to speed is equal to:

$$\varepsilon_T^v = \frac{v}{T} \cdot \frac{\partial T}{\partial v} = \frac{v}{l \cdot E} \cdot \frac{\partial T}{\partial v} = \zeta_l^v + \eta_q^v + \varepsilon_e^v \qquad (3)$$

where the elasticity of average travel distance to average travel speed on the facility/corridor is denoted:

$$\zeta_l^v = \frac{v}{l} \cdot \frac{\partial l}{\partial v}.$$

Hence, the change in total emissions is the combined effect of changing emissions rates, vehicle volumes, and travel distances with average speed. In order to understand emissions trends in terms of traffic variables, we need to measure *all three*changes: vehicle speeds and their impact on average emissions rates, vehicle volumes (or the number of peak-period vehicle trips), and distances traveled.

Another variable which impacts emissions is time (τ) – through the evolving vehicle fleet composition, vehicle volumes, and distance traveled over time. In this study, we use data on vehicle volumes, speeds, and travel distances over time (τ) but we assume a constant fleet composition; i.e. as in the UMR study we assume that fleet composition and emission rates are largely unaffected by τ. As later discussed, if fuel efficiency improves it is likely that the key results of this research are strengthened.

The range of ε_e^v is expected to be between -1.0 and 0.0 (though it will be positive at speeds above the emissions-optimum travel speed; usually, optimum travel speeds that minimize emissions are around the 60 mph rangeas shown in Section 4).The value of$\eta_q^v + \zeta_l^v$ can be expected to be between 0.0 and 1.0, depending on the time range[23]. The impacts of congestion (or travel speed reductions) on either distance traveled or number of trips is complex. For example, more congestion (reduced travel speeds) may lead to less traffic volume, but lowervolumes in turn lead to less congestion and some equilibrium is expected to be reached over time if there are no significant changes in the system. Regarding distance traveled, congestion can lead to a negative value of ζ_l^v if congestion encourages rerouting or sprawling; congestion can lead to a positive value of ζ_l^v, between 0.0 and 0.2 over time, if congestion is accompanied by higher densities and/or accessibility to alternative modes or destinations[24].

4 Emissions Sensitivity to Travel Speed

In this section we analytically assess the sensitivity of emissions rates to changes in average speed, in the context of the analytical framework presented above. Estimating ε_e^v allows us to compare it to ζ_l^v and η_q^v and so assess the importance of excluding changes in q and l from performance measures (see Equation 3).

The sensitivity of e to v is easily seen in Figure 1, which shows emissions versus speed curve *gradients* versus average travel speeds. The gradients are calculated using $\frac{\partial e}{\partial v}$ (with Equation 2 and α_i), then converting from mass rate changes to percentage rate changes for each 1 mph increase in v. The minimum emissions rate is when the gradient curve crosses the speed (horizontal) axis. The gradients in Figure 1 have low absolute values from 25-70 mph – meaning speed changes over this range have a small effect on emissions rates. While these gradients will differ by pollutant, vehicle type, and emissions model, research has shown that they are consistently small at moderate speeds [22].

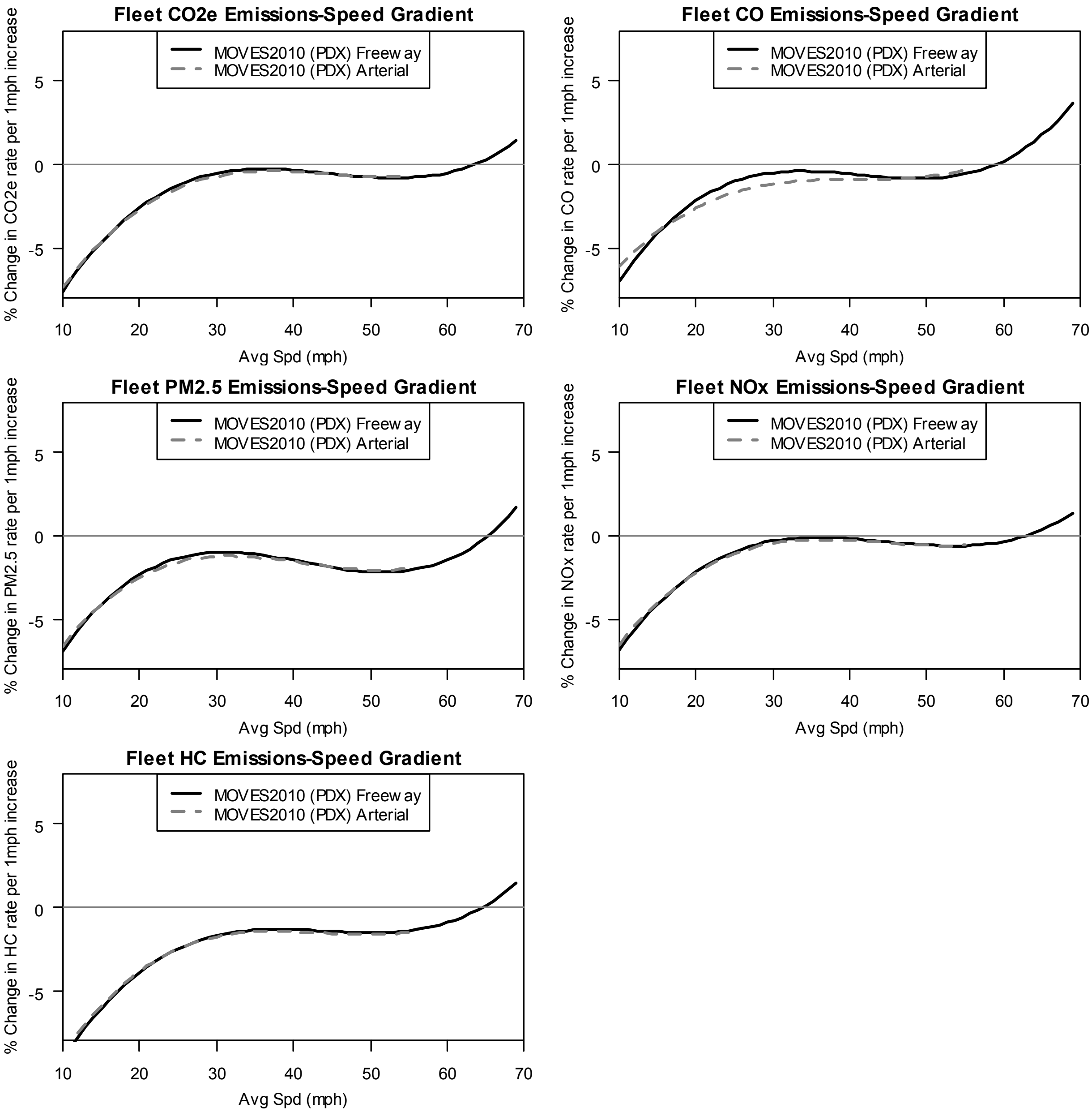

Figure 1.Freeway and Arterial Emissions Rate Gradients versus Average Speed

Figure 2 shows the calculated elasticity of freeway emissions rates to speed, ε_e^v (also the percent change in total emissions E with each percent change in speed v at a fixed value of VMT). The elasticity of emissions rates are not only highly non-linear but also very small for CO_2e, CO, and NO_x in the 30 mph to 45 mph range. This has significant implications for emissions changes due to congestion; in the 30 mph to 45 mph range, a significant reduction in travel speed can lead to only a small change in overall emissions for CO_2e, CO, and NO_x if the total travel volume is unchanged.

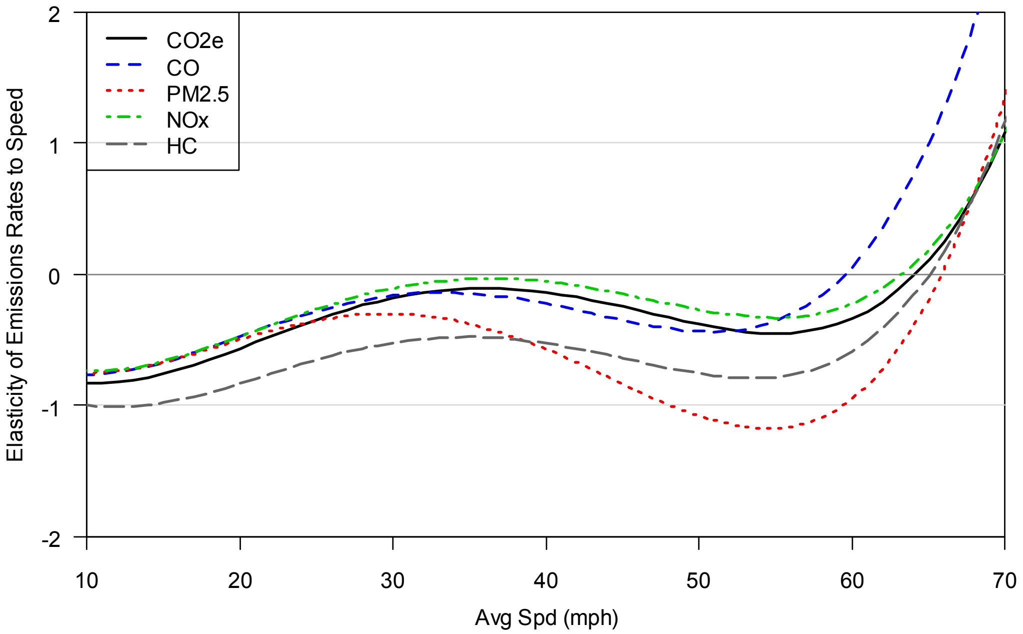

Figure 2. Elasticity of Freeway Emissions Rates to Speed, ε_e^v , by MOVES Model

The product of travel distance and traffic volumes is the VMT generated per unit of analysis time:

$$\mathrm{VMT} = q \cdot l \ .$$

Then from Equation 3 it follows that

$$\varepsilon_T^v = \zeta_l^v + \eta_q^v + \varepsilon_e^v = \eta_{VMT}^v + \varepsilon_e^v \ ,$$

where η_{VMT}^v is the elasticity of VMT to average travel speed. From the literature, η_{VMT}^v is expected to be between 0 and 1[23]. VHT per unit of analysis time is calculated

$$\mathrm{VHT} = \frac{\mathrm{VMT}}{v} = \frac{q \cdot l}{v} \ .$$

Similarly, the elasticity of VHT to v is

$$\eta_{\mathrm{VHT}}^v = \frac{v}{\mathrm{VHT}} \frac{\partial \mathrm{VHT}}{\partial v} = \eta_{VMT}^v - 1 \ ,$$

and so η_{VHT}^v is expected to be in the range of 0 to -1. It also follows that

$$\varepsilon_T^v = \eta_{VMT}^v + \varepsilon_e^v = \eta_{VHT}^v + 1 + \varepsilon_e^v \ .$$

These equations, coupled with Figure 2, show that as congestion grows and v decreases, the effect of changing VMT and VHT on emissions is at least as important as changing emissions rates. Thus, when speed-based mobility is the performance measure of interest, speed changes alone cannot be expected to reflect the full emissions impacts of congestion.

5 Congestion Performance Measures and MetropolitanEmissions

5.1 Performance across Cities

We first presentresults of emissions and performance measure estimates for the 101 cities of the UMR data tables in 2010.Estimated daily peak period CO_2e emissions per peak period traveler are shown in Figure 3 for 2010, with urban areas indicated by population category (Small: < ½ million, Medium: ½ - 1 million, Large: 1-3 million, and VeryLarge: > 3 million population). Comparing amongst urban areas inFigure 3, total emissions per peak period traveler and TTI have essentially no relationship, even among urban areas in the same population category.

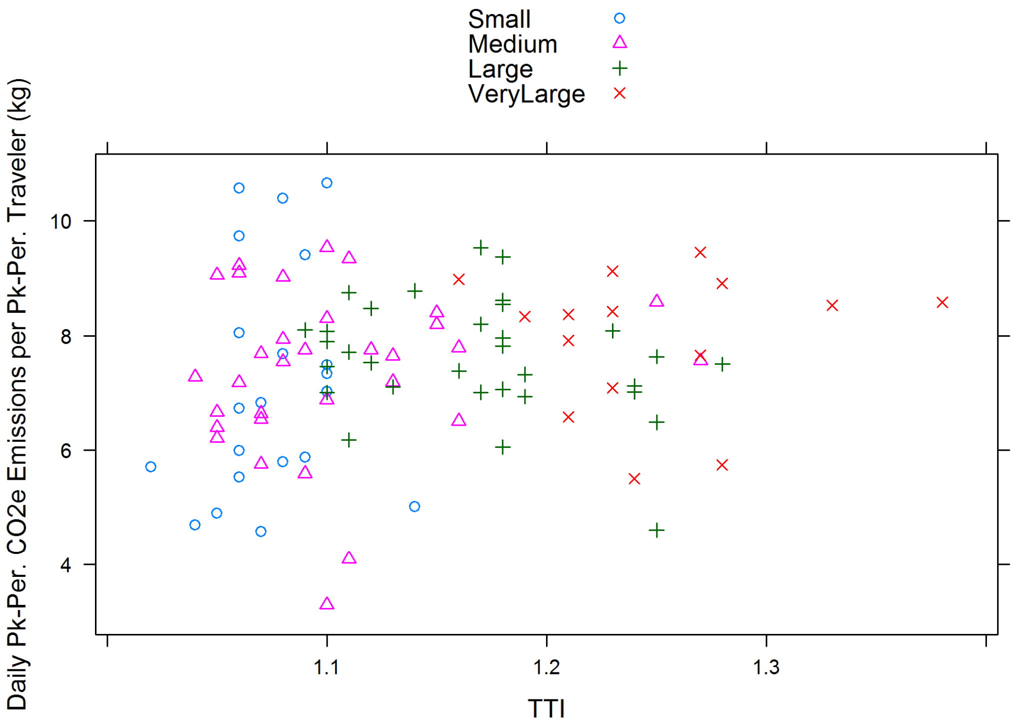

Figure 3. Daily Peak-Period CO_2e Emissions per Peak-Period Traveler versus TTI, Segmented by Urban Area Population Size

Figure 4 shows *total* daily peak period emissions (not per traveler or per capita) versus TTI, again segmented by urban area population size. Here total emissions increase somewhat withTTI and population. This is intuitive because the number of peak period travelers and population are expected both to be positively correlated with congestion levels and

TTIvalues.However, if we stratify by population category (as is done in Figure 4), we see that *within* population categories the TTI does not correlate with increasing total emissions. The two very high emitting urban areas are New York and Los Angeles, each with populations well above 10 million. As such, they better represent a fifth, “Extremely Large” population group, with high total emissions and TTI. What we see from the categorization in Figure 4 is that high total emissions are associated with larger population areas, not necessarily higher TTI’s (although those two are themselves correlated).

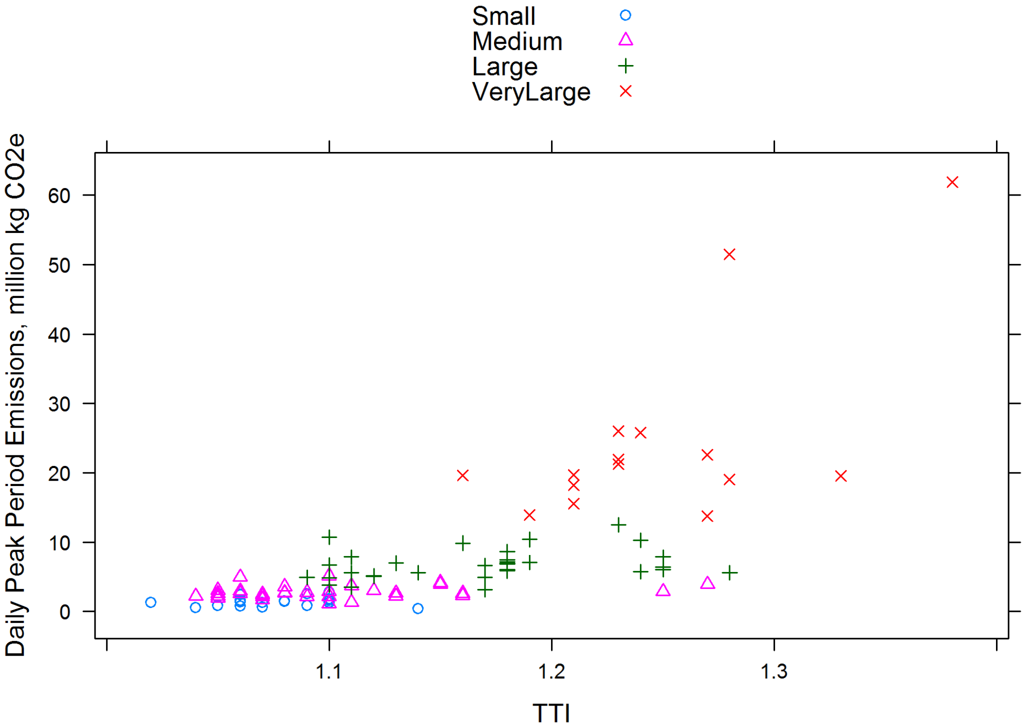

Figure 4. TotalDaily Peak-Period CO$_2$e Emissions versus TTI, Segmented by Urban Area Population Size

As stated above, the TTI is a mobility-based performance measure, normalized with respect to travel distance. As a contrast, Figure 5 shows VHT per peak period traveler and CO$_2$e emissions per peak-period traveler for the same urban areas in 2010. This figure shows strong correlation between VHT per traveler and emissions per traveler. Unlike the previous figure, the correlation holds even when urban areas are categorized by population size. Similar results appear when comparing per-traveler emissions with per-traveler VMT, or when comparing total emissions with total VHT or VMT (plots excluded).

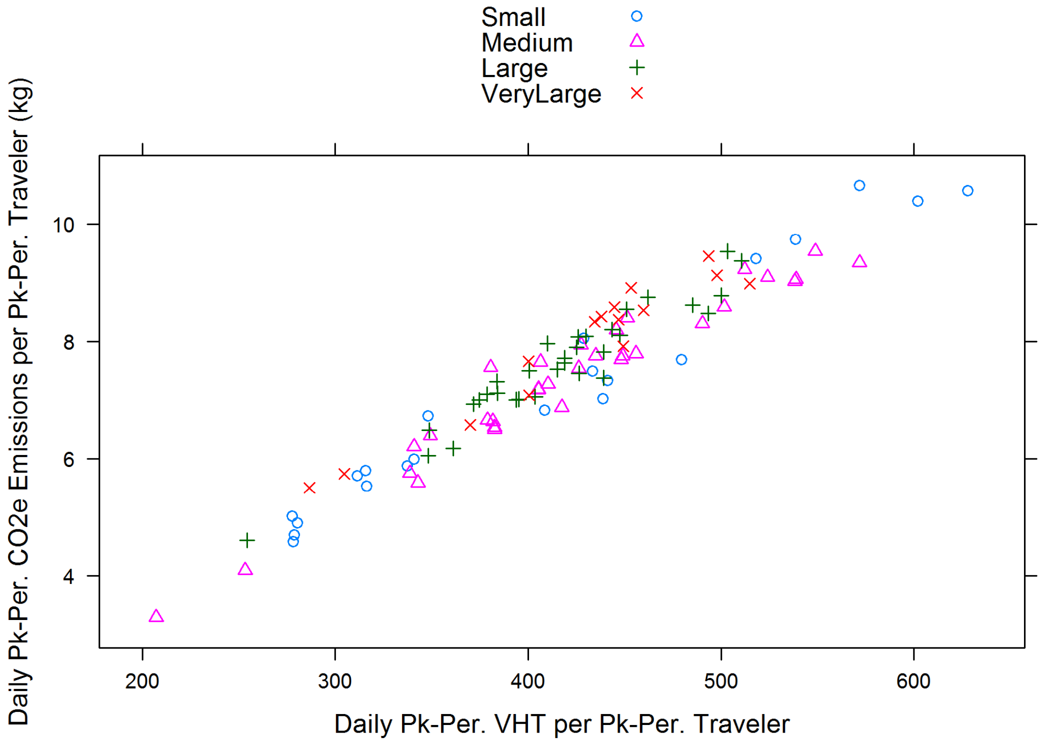

Figure 5.Daily Peak-Period CO_2e Emissions per Peak-Period Traveler versus Peak-Period VHT per Peak-Period Traveler, Segmented by Urban Area Population Size

These results are intuitive when we view them in the context of the analytical framework presented above. From Equation 1, it can be easily seen that the TTI does not directly reflect changes in vehicle volumes q or distance traveled l. The TTI can only directly reflect changes in vehicle emissions ratese (through changes in v). In terms of Equation 3, this means that the TTI neglects ζ_l^v and η_q^v. Hence, it is not surprising that there is a poor association between the TTI and emissions. When the change in vehicle travel demand (measured by VMT) outpaces the change in emissions rates, the TTI will not trend well against emissions (since the TTI does not measure VMT changes). On the other hand, performance measures that capture varying VMT would be more representative of emissions trends. In other words, TTI trends would likely correlate well with emissions if there are no or only small changes in VMT.

Since VHT $= \frac{q \cdot l}{v}$,VHT is directly influenced by all three components of Equation 3. So we can expect better association between VHT and emissions than between TTI and emissions (as reflected in Figure 5). Still, VHT is an imperfect correlate of emission because of the nonlinear relationship between $\frac{1}{v}$and $e(v)$.

Table 2shows calculated linear correlations between various roadway performance measures and peak-period CO_2e, NO_X, and $PM_{2.5}$ emissions (total and per peak period traveler). These correlations are calculated using the 101 cities in the UMR for 2010, as in the figures above. Cells shaded light gray indicate correlation coefficients with an absolute value between

0.5 and 0.75; cells shaded darker gray indicate correlation coefficients with an absolute value above 0.75. Similar results are obtained for CO and HC emissions (excluded for brevity).

Table 2. Linear Correlations Between MetropolitanEmissions and Roadway Performance Measures

	CO_2e		NO_x		$PM_{2.5}$	
	Total	per Traveler	Total	per Traveler	Total	per Traveler
TTI	0.701	0.128	0.701	0.101	0.702	0.258
VMT	1.000	0.126	1.000	0.107	0.999	0.217
VHT	0.999	0.123	0.999	0.103	0.999	0.217
Delay	0.961	0.009	0.961	-0.010	0.965	0.102
VMT/ traveler	0.064	0.990	0.065	0.996	0.056	0.918
VHT/ traveler	0.244	0.950	0.245	0.942	0.241	0.957
Delay/traveler	0.723	0.250	0.723	0.225	0.723	0.369
RCI	0.574	0.187	0.574	0.168	0.573	0.284
CSI	0.708	0.145	0.708	0.121	0.708	0.266
Rush Hours per Day	0.767	0.125	0.767	0.102	0.764	0.233
% Congestion (lane-miles)	0.390	-0.053	0.390	-0.074	0.392	0.068
% Congestion (VMT)	0.592	0.052	0.592	0.029	0.591	0.180
Peak period travelers	0.972	0.000	0.972	-0.018	0.970	0.089

From Table 2, total emissions correlate most strongly with VMT, VHT, total delay, and the number of peak period travelers. These correlations are consistent across pollutants. Total emissions also seem to correlate relatively well with TTI, but the association is spurious because(as shown in Figure 4) the stronger association seems to be between total emissions and city size. This is further evidenced by the high correlation coefficient between total emissions and the number of peak period travelers.

Because of the confounding factor of city size, the more interesting correlations in Table 2 are for emissions per traveler. This acts as a control for city size, allowing us to assess relationships between emissions and transportation performance measures across cities of different sizes. Emissions per traveler only correlate strongly with VMT per traveler and VHT per traveler. These two performance measures account for varying travel distances per traveler (q and l). Controlling for city size, the correlation between total emissions and TTI is much lower than 0.701. Similarly, we see that the correlation between total delay and total emissions does not hold when we normalize to the number of travelers. The mobility-based performance measures (TTI, Delay, and CSI) do not correlate with emissions per traveler, nor do performance measures related to congestion extent (rush hours, percent congested, and RCI) or total travel performance measures (VMT and VHT).

This is a highly macroscopic approach to studying congestion and emissions, but it is useful to look at general relationships across a diverse set of 101 US cities. In the next section we take a different approach to metropolitan comparisons between emissions and roadway performance measures by looking at changes over time.

5.2 Performance over Time

We next present results for metropolitan-level trends. As stated above, for metropolitan comparisons over time the emissions rate parameters $\alpha_i$are fixed at the 2010 value, so we are not assessing the impacts of an evolving vehicle fleet, only the impacts of changing travel conditions. The objective is not to estimate absolute mass emissions (only changes), so evolving α_i would only introduce a potentially confounding variable. We present results here for CO_2e only because Table 2 indicates that correlations for CO_2e, NO_x, and $PM_{2.5}$ are very similar.

Figure 6 shows the performance measure results for Portland, Oregon for the years 1982-2010, normalized to 1982 values. CO_2e Emissions, VHT, and VMT are all normalized to the number of peak period travelers (which grew steadily over this time period). While emissions, travel time, and VMT all track closely, TTI diverges – in the opposite direction after 1993. This is because while delay per mile of travel has continually increased or stayed constant, *automobile* travel distances per *peak-period traveler* (related toζ_l^v) have fallen since the early 1990's and have outweighed the impact of increased emissions rates per vehicle (related toε_e^v). However, if increased congestion had been accompanied with increased travel distances (for example due to urban sprawl or rerouting), Figure 6 may have shown a spurious relationship between TTI and total emissions.

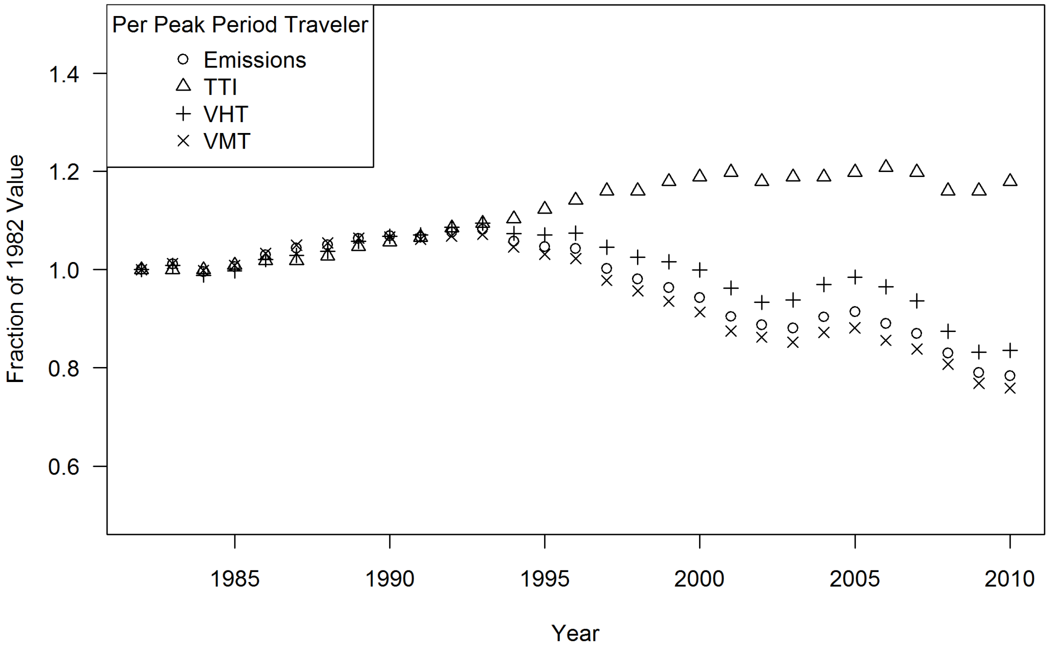

Figure 6. Changes over Time in Performance per Peak-Period Traveler for Portland, OR

Figure 7 presents a similar comparison for all 101 urban areas in the UMR for the ten-year time interval from 2000 to 2010. Figure 7 compares changes in TTI, VHT per peak period traveler, and VMT per peak period traveler with changes in emissions per peak period traveler for the 10-year period. In agreement with preceding results, emissions are much more correlated with VMT and VHT than TTI.

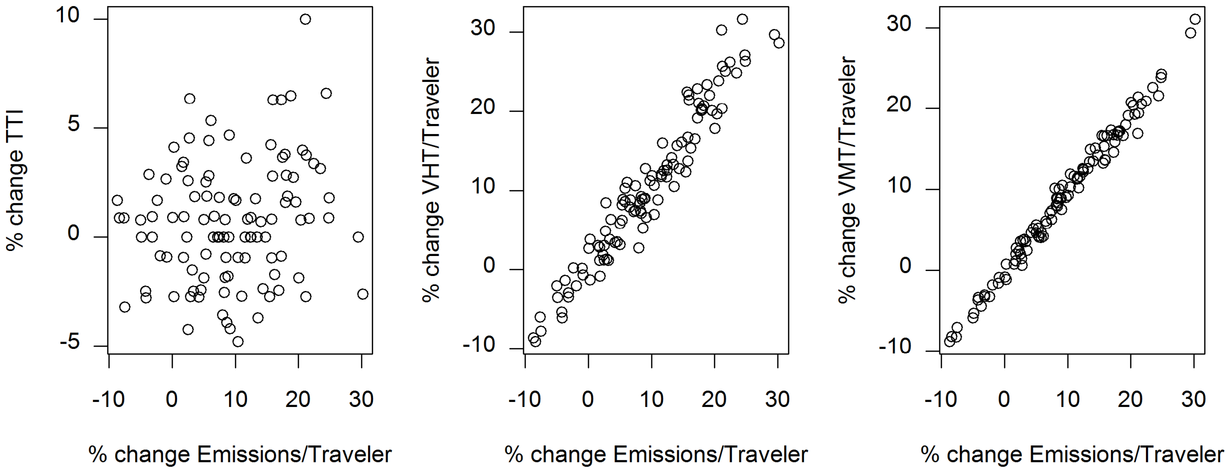

Figure 7. Comparison of Changes in TTI, VHT per Peak-Period Traveler, and VMT per Peak-Period Traveler versus Changes in CO₂e Emissions per Peak-Period Traveler from2000 to 2010 for 101 Urban Areas in the UMR

These figures show that metropolitan-level performance measures related to the amount of travel (VMT or VHT) are better indicators of CO_2e emissions trends from peak-period travel than traditional mobility measures. This is particularly true if we control for city size or population growth by normalizing to the number of travelers. The next section uses the analytical frame work to further explore the link between roadway performance measures and emissions.

6 Corridor Study

The empirical analysis in Section 5 uses highly aggregated speed and travel volume data at the metropolitan level. As a consideration of finer spatial scales, this section presents the results of a corridor study on performance measures. The higher-resolution data also allows calculation of reliability-based roadway performance measures such as the PTI and BTI.

Table 3 shows calculated linear correlations between roadway performance measures and total daily emissions on the corridor at three temporal aggregations (hourly, daily, and monthly). The cells with light gray shading indicate absolute value of correlation coefficients between 0.5 and 0.75; cells shaded darker gray indicate correlation coefficients with an absolute value above 0.75. The TTI, PTI, and BTI are calculated using weekday peak period data only. Hours, days and months with incomplete data are excluded. The monthly data are averaged over weekdays.

For the monthly data the TTI values range from 1.18 to 1.51, PTI from 1.49 to 2.65, and BTI from 0.20 to 1.03. Hourly VMT and VHT ranged from 1,008 to 54,658 vehicle-miles and from 19 to 2,134 vehicle-hours, respectively. Daily VMT ranged from 298,959 to 673,959 vehicle-miles and daily VHT ranged from 5,054to 16,177 vehicle-hours on the 14-mile corridor. Daily total CO_2e emissions ranged from 147 to 361Mg.

Table 3. Linear Correlations Between Corridor Emissions and Performance Measures

		CO_2e	NO_x	$PM_{2.5}$	HC	CO
Monthly Data (N=31)	VMT	0.981	0.990	0.911	0.915	0.983
	VHT	0.910	0.884	0.975	0.978	0.905
	Delay (veh-hr)	0.494	0.443	0.671	0.671	0.485
	TTI	0.338	0.283	0.534	0.533	0.328
	PTI	0.397	0.361	0.494	0.522	0.393
	BTI	0.364	0.341	0.410	0.446	0.363
Daily Data (N=621)	VMT	0.972	0.986	0.886	0.881	0.974
	VHT	0.884	0.850	0.964	0.973	0.879
	Delay (veh-hr)	0.499	0.438	0.685	0.701	0.490
	TTI	0.403	0.340	0.595	0.616	0.394
Hourly Data (N=11,553)	VMT	0.984	0.992	0.934	0.927	0.984
	VHT	0.918	0.896	0.967	0.978	0.917
	Delay (veh-hr)	0.536	0.491	0.670	0.696	0.533
	Travel Time	0.410	0.365	0.531	0.573	0.405

From the correlation coefficients in Table 3 we see thatat the corridor level VMT and VHT are still the measures most correlated with emissions. The reliability-based performance measures show similar correlations to the purely speed-based measure (TTI). The pollutants that are more sensitive to speed ($PM_{2.5}$ and HC – see Figure 2) are more correlated with VHT than VMT (and also have higher correlations with delay, TTI, and travel time). The correlations in Table 3reflect that PTI and BTI are more correlated with VMT than TTI is. Furthermore, TTI is more correlated with VHT than PTI or BTI are. Although only studied on a single corridor, this analysis shows that the associations in Table 2 are consistent with results from higher-resolution data.

7 Conclusions

This paper represents a step toward better understanding of the connections between congestion, automobile travel demand,and emissions. An analysis of several traffic-related performance measures shows that for reflecting emissions impacts, VMT is an essential component of performance. Hence, using a VMT-insensitive performance measure such as the TTI to indicate total emissions performance trends is potentially large.Neglecting variable automobile travel demand can even change the direction of the relationship between roadway performance measures and emissions.

Although heavier congestion levels increase emissions rates per vehicle-mile, the data show that the travel demand volume is the dominant factor behind total emissions increases, not travel speed. Thus, alternative congestion measures based on travel distance or travel time are preferable indicators of emissions trends to speed or delay. Congestion extent measures such as the Roadway Congestion Index or percent congestion are also poorly correlated with emissions.

Note that this is not a critique *per se* of mobility measures, which are not designed to reflect emissions trends. Rather, the critique focuses on the unproved, commonly assumed linkage between congestion and emissions (described in the introduction to this paper); this common misconception usually leads decision makers, the media, and the public to conflate the two and assume that indicators of one are indicative of the other.The results in this paper simply show that mobility measures should not be associated with emissions performance.

An assumption throughout the analysis presented in this paper is that vehicle fleet composition and fuel efficiency or emissions rates do not change over time. In reality, emission rates $e(v, \tau)$and vehicle fleet composition are also functions of time τ. However, this assumption is conservative. If fuel efficiency and technology improve such that emissions rates decrease over time, then we can expect poorer correlations in trends between speed-based mobility measures and emissions performance. Furthermore, if emissions *sensitivity* to speed (ε_e^v) decreases over time (as suggested by some research [25], [26]), then in the future we can expect even poorer correlations between mobility and emissions performance measures.

One other point to note is that in this paper we look at either total emissions or emissions per peak-period traveler (using any mode). Normalization to the number of travelers allows comparisons across cities of different sizes, while still allowing for variations in travel characteristics such as mode and trip lengths. Normalization to VMT is not used because VMT is considered a basic output of the transportation system, whereas the number of travelers is a basic transportation demand indicator.

Finally, this is a macroscopic analysis investigating the broad relationship between congestion and emissions in varying contexts. It admittedly neglects some unique emissions effects of microscopic traffic features and some indirect, higher-order impacts of congestion as well as the evolution of fleet composition and technology. Nonetheless, the results show quantitative comparisons based on an expansive data set and provide a better understanding of the relationships between transportation performance measures and emissions. Topics for future research include an arterial corridor study and separation of effects between different vehicle classes.

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