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ABSTRACT

We determine the environmental benefit of using electric buses rather than diesel or CNG for urban transit. For diesel and CNG we calculate air pollution damages by combining emission rates with damage valuations from the AP3 integrated assessment model and the social cost of carbon. For electric buses we calculate air pollution damages by combining the damage valuations with estimates of the marginal increase in emissions from electricity usage. The environmental benefit is positive on average across all counties in the contiguous U.S. when comparing electric to either diesel or CNG. The environmental benefit of operating an electric bus fleet (rather than diesel) is about $65 million per year in Los Angeles and above $10 million per year in six other MSAs. Including the environmental benefit, we calculate the net present value (NPV) of bus investment. Relative to diesel, the NPV benefit of an electric bus is positive in about two thirds of urban counties. Relative to CNG, the NPV benefit is negative in all counties.

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1 Introduction

In the United States, as in many parts of the world, the surface transportation fleet is in the early stages of electrification. To date, much of the innovation and market penetration of electric vehicles has occurred in the light-duty vehicle market. Accordingly, research exploring the relative environmental impacts of internal combustion and electric technology typically focuses on light-duty vehicles.[1] However, cars are only one aspect of the surface transportation infrastructure that could be electrified. Some city buses, trolleys, and trains currently rely on overhead power lines or electrified rails. Elon Musk recently unveiled plans for a Tesla long-haul semi-truck. Broadly based technological change (further advances in battery technology, wireless charging, and autonomous driving) may open new possibilities for buses and trains as well as for short-haul delivery, commercial and heavy-duty trucking, and other transportation modes. As alternative technologies develop and mature, the possibilities for electrification in the transport sector are vast.

In light of these emerging possibilities for electrification into the transportation sector, the present analysis examines buses used for mass-transit.[2] We compare traditional diesel, compressed natural gas (CNG), and electric buses. We determine the environmental benefit of bus electrification by comparing the damages from local air pollution and greenhouse gas emissions from the electric buses to the corresponding damages from the forgone internal combustion-powered buses. (Because there are still thousands of older diesel buses in use, we also demonstrate that any one of the new bus technologies is a vast improvement over the antiquated models.) We also conduct a net present value (NPV) comparison of new buses inclusive of capital costs, operations and maintenance expenditures, and external costs due to pollution damages. We focus on the case of urban buses for three reasons. First, proponents of mass-transit claim that it is a means to reduce individual vehicle use and hence, total urban emissions. Our assessment of air pollution damages could affect the merits of this claim moving forward. Second, buses are relied on heavily in cities where local air pollution causes

[1] Prior analyses include Archsmith et al. (2015), Graff Zivin et al. (2014), Holland et al. (2016), Holland et al. (2019), Li et al. (2017), and Michalek et al. (2011).

[2] See Tong et al. (2017) for a review of previous studies of air pollution from various alternative fuel buses. Tong et al. (2017) analyze electric buses but use average damages from electric power plants rather than marginal damages.

large damages. In this context, identifying the least cost technology, inclusive of external costs, stands to yield potentially large net benefits per vehicle. Third, this vehicle class lies at the electrification frontier. Thus, guidance in the form of a comparative policy analysis between internal combustion buses and electric buses may help states and metropolitan areas prioritize investment in electrification.

Conceptually, it is straightforward to calculate the environmental benefit of switching from natural gas or diesel powered modes of transportation to the substitute electric powered mode of transportation. One simply compares the damages from emissions from the tailpipe to the damages from the emissions from the smokestack of the power plant providing energy to charge the electric vehicle. In practice, there are several difficulties to carrying out this calculation, some of which have not been satisfactorily addressed by the previous literature.

First, both electric and conventional transportation produce emissions of a variety of pollutants. A complete assessment must analyze these multiple pollutants. A multipollutant framework necessitates a modeling apparatus that tracks both local air pollutants and greenhouse gases. For local air pollution, we employ the AP3 model (Clay et al., 2019; Holland et al., 2019) which is an updated version of the AP2 model (Muller, 2014; Holland et al., 2016). For greenhouse gases, we use the social cost of carbon from the federal government interagency working group meta-analysis (USIAWG, 2016). This distinction among pollution types raises the second empirical challenge; transportation emissions occur at different locations. While greenhouse gases have the same effects regardless of their location, the effects of emissions of local pollutants, e.g., particulate matter, depend on where they are emitted. Thus, we use AP3 to calculate impacts ($/mile) by county using spatially tailored estimates of the marginal damage of emissions.[3] These values reflect heterogeneity in exposure (e.g., whether emissions occur in cities or rural locations) and variation in atmospheric conditions which dictate the fate and transport of emissions. Crucially, even in a counterfactual simulation comparing conventional buses to electric ones in which use of the vehicle takes place in the same county, emissions are produced in different locations because the regional power grid supplies energy for the electric bus, whereas diesel emissions are released from the vehicle itself. This consideration leads to the third challenge: assessing emissions from electric

[3]See the Appendix for details on AP3.

transportation requires assigning emissions at power plants to electricity use at various locations. We tackle this problem using a reduced-form regression approach similar to that in Holland et al. (2018). Specifically, plant-level hourly damages (emissions times damage valuation) are aggregated across power plants in an interconnection and then regressed on hourly electricity demand to give the marginal damages from an increase in demand.

Putting these three pieces together yields the first complete county level comparison of electric vs non-electric transit buses.[4] On average across the counties, electric buses create less air pollution damages (11 cents/mile) than CNG buses (12 cents/mile) which in turn create less air pollution damages than diesel buses (15 cents/mile). These averages mask considerable heterogeneity, however. There are counties in which diesel is cleaner than electric, and counties in which CNG is cleaner than electric. And there are some counties in which the benefits of electric buses are quite large (damages are 63 cents/mile less than diesel in Los Angeles). We also calculate the air pollution benefit at the metropolitan statistical area (MSA) level rather than the county level. For this analysis, we consider replacing the entire current fleet (which is essentially a mix of new and old diesel buses) with a brand new fleet of either electric, diesel, or CNG buses. Comparing a fleet of electric buses to a fleet of new diesel buses generates annual benefits of $65 million in the Los Angeles MSA and more than $10 million in six other MSAs. Our final set of calculations determine the NPV benefit of an investment in an electric bus rather than a non-electric bus. Electric buses are more expensive to purchase, but tend to have lower ongoing costs. On average, the NPV benefit of such an investment is positive if the forgone bus is diesel and negative if the forgone bus is CNG. Again there is significant heterogeneity, but the NPV benefit of electric versus CNG is negative in all counties.

Both the transport and the power generation sector face considerable environmental regulation. In the United States, traditional measures to mitigate pollution from the transportation sector are a mix of technology and performance standards. Most relevant to the present analysis is the requirement, phased in between 2006 and 2010, that heavy-duty on road vehicles (inclusive of transit buses) use diesel fuel with a very low sulfur content.

[4] Previous studies of alternative fuel buses include Cooney et al. (2013), Noel and McCormack (2014), Shirazi et al. (2015), Aber (2016), Lajunen and Lipman (2016), Mahmoud et al. (2016), and Tong et al. (2017).

Numerous regulations apply to stationary point sources, including fossil fuel-fired power stations. These policies required or induced firms to adopt pollution abatement technology and to use less pollution intensive fuels such as low sulfur coal and natural gas. Hence, both internal combustion vehicles and, by virtue of extant rules governing emissions from power stations, electric vehicles face environmental policy constraints. As such, the comparison between these technologies reflects the current regulatory landscape. Importantly, as new policies emerge, and enforcement of existing policies changes over time, the outcome of such a comparison will also change. This is an especially important point considering meaningful efforts to mitigate future climate change are also likely to affect both sectors.

2 Environmental benefits of electric buses

The environmental benefits to air pollution of bus electrification depend on the damages from the forgone non-electric bus relative to the damages from the electric bus. Air pollution damages from non-electric buses come from emissions of a variety of pollutants directly from the tailpipes of the buses. As described below, we calculate emissions rates (grams per mile) and then multiply these by location-specific damage valuations ($ per gram) of each pollutant. Summing across pollutants gives the air pollution damages for a non-electric bus. Air pollution from electric buses comes from the power plants that generate the electricity to charge the buses. To assess these damages, we first determine the *marginal damages* from consuming a unit of electricity ($ per kWh). Multiplying the marginal damages by the electricity consumption (kWh per mile) gives the location-specific air pollution damages for an electric bus.

For consistency in the comparison between electric and non-electric buses, we utilize data from the testing protocols at the Altoona testing facility that tests both types of buses.[5] The facility tests fuel economy on a test track and tests emissions on a dynamometer for simulated transit duty cycles.[6] The tests are detailed and accurate and are likely to well

[5]The Altoona testing facility is the Larson Transportation Institute's Bus Research and Testing Center, located in Altoona, Pennsylvania. This testing center was established in 1989 with funding provided by the Federal Transit Administration under the the Surface Transportation and Uniform Relocation Assistance Act (STURAA; Public Law 100-17) of 1987.

[6]The facility also tests safety, structural integrity, durability, performance, maintainability, and noise.

represent comparable fuel use and emissions from actual driving of both non-electric and electric buses.

2.1 Non-electric bus damages

Lowell (2013) aggregates fuel economy and emissions tests from the Altoona facility for a variety of non-electric buses. The buses met the latest federal emissions standards (last revised in 2010) and thus are reflective of emissions of newly purchased buses. Table 1 shows average fuel economy and emissions rates from Lowell (2013) for two types of buses: "Diesel" and compressed natural gas "CNG" buses. The emissions rates for NO_X, $PM_{2.5}$, and VOCs (volatile organic compounds) come directly from the emissions tests while SO_2 and CO_2 emissions rates are calculated from the fuel economy. The SO_2 emissions assume ultra low sulfur diesel (15 parts per million sulfur) for Diesel and negligible SO_2 emissions for CNG. The CO_2 emissions assume 22.38 lbs of CO_2 per gallon of diesel fuel. CNG buses have lower emissions than Diesel for all local pollutants except VOCs. Natural gas has lower carbon content than diesel fuel, but this advantage is offset by lower fuel economy leading to similar MPGe and CO_2 per mile for CNG and Diesel.

The environmental benefit of a new electric bus depends on the forgone new non-electric bus. However, approximately 35 percent of buses cataloged in the 2018 National Transit Database are 10 years or older.[7] To calculate the benefit of replacing these older buses, we collect data on emissions from the existing bus fleet from the meta analysis in Cooper et al. (2012). Table 1 shows the "Old Diesel" fuel economy and emissions rates. The SO_2 emissions rates are not substantially higher, because we assume the Old Diesel buses also use low sulfur diesel. However, the NO_X emissions are dramatically higher so there will be substantial benefits from replacing the Old Diesel buses in regions where NO_X emissions are particularly harmful. Of course, these benefits would accrue whether the Old Diesel bus were replaced by a new non-electric or electric bus.

Damages depend not only on emissions of each pollutant but on the relative harm of the various pollutants which may differ by location. For the local pollutants, we use the

[7] See the Online Appendix for the description of this calculation and the spatial distribution of these old buses.

Table 1: Emissions rates for non-electric buses

	MPGe	NO_X	$PM_{2.5}$	VOCs	SO_2	CO_2
Diesel	4.68	1.178	0.0065	0.0258	0.020	2171
CNG	4.62	0.465	NR	0.0283	NR	2197
Old Diesel	3.79	19.619	0.493	0.659	0.0249	2678

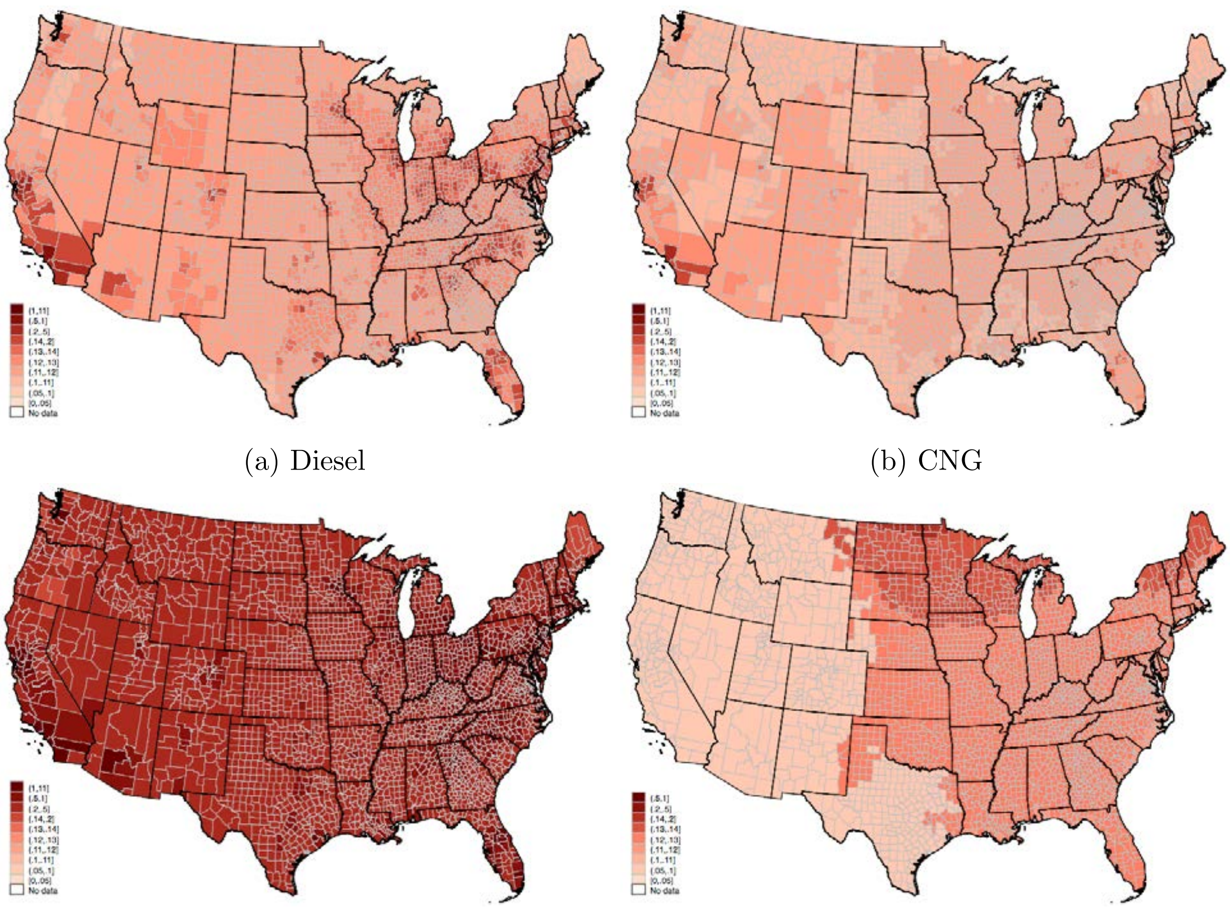
Notes: Emissions rates in grams per mile calculated from Lowell (2013) and Cooper et al. (2012). "MPGe" is miles per gallon diesel equivalent. "NR" is not reported.

AP3 integrated assessment model to determine the county-specific damage valuations ($ per gram) for each pollutant (Clay et al. 2019). AP3 uses annual average meteorological data to map the flow of emissions over space, chemistry to specify how primary pollutants interact in the atmosphere to create ambient concentrations of secondary pollutants, epidemiology to map pollution concentrations into increased mortality, and finally economics to assign dollar values of damages using the value of a statistical life. For CO_2, the damage valuation is the social cost of carbon (SCC) adjusted to 2017 of $43.50 per ton of CO_2 from the US inter-agency working group meta-analysis (USIAWG, 2016). The county-specific damage valuation per mile of each bus type is the product of the damage valuation and the emission rates in Table 1 summed across the five pollutants.

Figure 1a-1c show the air pollution damages from driving a non-electric bus one mile in each of the 3109 counties in the contiguous U.S. Figure 1a shows the air pollution damages from driving a new diesel bus. Damages are largest in counties that contain large urban areas, and there is significant spatial heterogeneity despite the fact that a large share of the damages are from CO_2, a global pollutant. Figure 1b shows the air pollution damages from driving a new CNG bus. CNG buses generally have lower damages than Diesel buses almost everywhere and also have significant spatial heterogeneity. Figure 1c shows the air pollution damages from driving an Old Diesel bus. As we would expect from their emission rates, damages from old diesel buses are quite large almost everywhere.

2.2 Electric bus damages

Our comparable electric bus to the Diesel and CNG buses above is the Proterra Catalyst FC battery electric bus. Proterra is the largest manufacturer of electric buses in the US, and



(a) Diesel

(b) CNG

(c) Old Diesel

(d) Electric

Figure 1: Air Pollution Damages ($ per mile)

this bus used an average of 2.185 kWh per mile in the Altoona test facility in 2018.[8] Because it is expected that electric buses will consume more electricity per mile in very hot and very cold weather, we apply the temperature correction used by Holland et al. (2016) to adjust the electricity consumption per mile according to the average monthly temperature in each county.[9,10] Using this correction, the average electricity consumption increases to 2.33 kWh per mile.

The air pollution damage from bus electricity consumption is the marginal damage from consuming a unit of electricity ($ per kWh). Following Holland et al. (2018)'s methodology, we first calculate damages from emissions of the main four pollutants, SO_2, NO_X, $PM_{2.5}$ and CO_2 at each power plant in the contiguous U.S for every hour in the year 2017.[11] Hourly emissions of SO_2, NO_X, and CO_2 are reported by the EPA's Continuous Emissions Monitoring System (CEMS) for approximately 1500 power plants. Hourly emissions of $PM_{2.5}$ are imputed from the emissions rates in the National Emissions Inventory and from hourly electricity generation from CEMS. Multiplying emissions by the SCC or by power plant specific damage valuations per unit of emissions from the AP3 model gives damages for each hour at each power plant. We then determine marginal damages by regressing total damages on electricity usage.

To determine the level of aggregation for the regressions, it is helpful to consider the structure of the U.S. electricity grid. The grid is divided into three interconnections: East, West, and Texas. Very little power flows across the interconnection boundaries, and some studies use the interconnection as the unit of analysis for determining marginal damage (Holland et al. 2018). Although it is technically feasible for electricity to flow freely within an

[8]The test procedure is based on simulated driving routes. Two NREL studies analyze Proterra electric bus use over actual transit routes over longer time frames in southern California (Eudy and Jeffers, 2017) and Seattle, WA (Eudy and Jeffers, 2018) and find efficiencies of 2.15 to 2.36 kWh per mile. Other buses tested in the Altoona test facility (and their efficiencies) include: Gillig (2.268 kWh per mile) in 2018; Nova L920 (2.024 kWh per mile) in 2018; Proterra Cat E2 (2.203 kWh per mile) in 2017; Proterra BE40 (1.70 kWh per mile) in 2015; Proterra BE35 (1.73 kWh per mile) in 2012, BYD K7 (1.36 kWh per mile for a 30 ft. bus) in 2017, and BYD Ebus (1.99 kWh per mile) in 2014.

[9]The test facility holds temperature constant at 73°. The NREL studies report slightly higher kWh per mile in Seattle than in southern California, possibly due to temperature differences.

[10]The temperature correction assumes no penalty at an average daily temperature of 68°. For each month, the kWh per mile is penalized based on the difference between 68°and the average daily temperature of the month. We then average across months.

[11]Holland et al. (2018) document a substantial decline in marginal damages so we focus on their most recent year.

interconnection, it is likely that congestion in the transmission network would lead marginal damages to differ across locations within an interconnection at least during some hours of the day. In response to this, some studies disaggregate electricity usage by North American Electric Reliability Corporation (NERC) regions (Holland et al. 2016) and others drill down further into NERC sub regions (Sexton et al. 2019). Ideally, we would like to use as small a geographic region as possible to measure marginal damages. But there is a trade-off. Due to correlation of electricity usage across NERC regions, and particularly sub-regions, it is difficult to precisely estimate regression models at these spatial scales (Callaway et al. Forthcoming). Here we aggregate damages and electricity usage to the interconnection level and estimate marginal damages for the interconnection.

Specifically, let D_t be the total damages in the interconnection from emissions in hour t. This variable is the sum of damages from all four pollutants and all power plants in the interconnection. The main estimating equation is

$$D_t = \beta Load_t + \alpha_{mh} + \epsilon_t, \tag{1}$$

where $Load_t$ is electricity usage in the interconnnection in hour t and α_{mh} are month of sample times hour fixed effects (1 year * 12 months * 24 hours fixed effects). The coefficient of interest is β, which is the marginal damage from an increase in electricity usage. We specify units such that marginal damages are in cents per kWh and estimate Newey-West standard errors using 48 hour lags.[12] The regressions are unweighted which assumes an equal probability of charging the buses across all hours of the year.

The results from estimating (1) are shown in Table 2. The "Total" column shows the main results. Marginal damages from electricity consumption range from 2.8 cents per kWh in the West to 5.3 cents per kWh in the East. These marginal damages are substantial relative to retail electricity prices.[13] The other columns decompose the estimates into marginal damages from global (CO_2) and local ($PM_{2.5}$, SO_2, NO_X) pollutants by replacing the total damages in (1) with damages from a single pollutant or a subset of the pollutants. The decomposition

[12] All valuations are in 2014 dollars.

[13] Residential electricity prices averaged 13 cents per kWh in 2019. https://www.eia.gov/energyexplained/electricity/prices-and-factors-affecting-prices.php

into global versus local pollution shows that global pollutant marginal damages are highest in the East but are similar across the regions. Local pollutant marginal damages are substantial in the East with the bulk of the marginal damage from SO_2 emissions. The West has the lowest local pollutant marginal damages primarily due to lower marginal damages from SO_2 emissions. Thus the geographic variation in marginal damages of electricity consumption arises from variation in marginal damages from both global and local pollution.

Table 2: Estimates of marginal damages from electricity consumption (2017)

Interconnection	Total	Global	Local	SO_2	NO_X	$PM_{2.5}$
East	5.336	2.625	2.711	1.850	0.483	0.378
	(0.168)	(0.048)	(0.129)	(0.117)	(0.015)	(0.007)
West	2.789	2.048	0.741	0.222	0.259	0.259
	(0.074)	(0.056)	(0.022)	(0.013)	(0.010)	(0.011)
Texas	3.537	2.055	1.482	1.069	0.222	0.191
	(0.171)	(0.087)	(0.102)	(0.093)	(0.010)	(0.008)

Notes: Newy-West standard errors (48 hour lag) in parentheses. Dependent variable is hourly damages from the reported pollutant(s) in an interconnection. "Total" is sum of all pollutants, i.e., of global and local. "Global" is CO_2. "Local" is sum of SO_2, NO_X, and $PM_{2.5}$. Coefficient estimates in cents per kWh. Regressions include month of sample by hour fixed effects.

The air pollution damages from driving an electric bus in each county is the product of the temperature-adjusted electricity consumption per mile and the interconnection-specific marginal damage per kWh. Figure 1d shows the air pollution damages from driving an electric bus one mile for each county in the contiguous U.S. There are significant differences across the interconnections. In particular, damages per mile from electric buses are substantially lower in the West and Texas than in the East. The figure also illustrates the electricity consumption penalty from extreme temperatures, which results in higher damages in northern counties.

2.3 Comparisons and Environmental Benefits

The maps in Figures 1a-1d show the air pollution damages from driving non-electric and electric buses in each county. Comparing the maps for Diesel and Electric shows that the environmental benefits of bus electrification relative to diesel are likely to be most significant in urban areas and in the West and Texas. However, electric buses would result in higher damages in some counties primarily in the northern Midwest and Plains states. Comparing the maps for CNG and Electric shows a similar distribution of environmental benefits of bus electrification relative to CNG. Comparing the maps for Old Diesel and the new buses shows that there would be substantial environmental benefits from replacing old diesel buses with any of the new buses.

Although maps are useful for illustrating the geographic distribution of environmental benefits, they may not capture the locations where buses are actually used and needed. Table 3 presents summary statistics for damage and environmental benefits weighted by estimated bus miles for each county from the US EPA MOVES model.[14] The mean damage for the Diesel bus is \$0.151 per mile and ranges from a minimum of \$0.106 per mile, which largely reflects the CO_2 damages, to a maximum of \$0.696 per mile, which reflects the high damages of local air pollution in Los Angeles. To put these damages in context, multiplying by the MPGe implies a mean damage of \$0.70 per gallon with a range from \$0.50 to \$3.30 per gallon. Mean damage from CNG buses (\$0.123 per mile) is lower than Diesel and the range of damages is smaller reflecting the lower damages from local pollutants particularly NO_X and SO_2. The Old Diesel bus is about seven times more damaging than the other bus types and has a maximum damage of a remarkable ten dollars per mile. The Electric bus has the lowest mean damage (\$0.112 per mile) and the narrowest range of damages suggesting the potential for environmental benefits from bus electrification.

Although electric buses have lower damages on average, this does not imply that they would yield environmental benefits in each county. The bottom rows of Table 3 show summary statistics of the environmental benefit (the difference in damages) of an electric bus relative to the non-electric alternatives. On average electric buses generate a positive environmental benefit relative to both diesel (\$0.039) and CNG (\$0.011 per mile). In a few counties, e.g., Los Angeles county, this benefit is quite large (up to 63 cents per mile). A few counties would see negative environmental benefits from bus electrification, but the environmental benefit relative to Diesel is positive in the majority of counties (the 18th percentile

[14]The MOVES model estimates VMT for each US county for a variety of vehicle categories. The bus miles category includes both transit and school buses.

Table 3: Damages By Bus Type and Environmental Benefit of Electric Buses ($ per mile)

	Mean	Std. Dev.	Min	Max
Diesel	0.151	0.067	0.106	0.696
CNG	0.123	0.025	0.106	0.330
Old Diesel	1.003	1.194	0.167	10.381
Electric	0.112	0.023	0.061	0.141
Benefit of Electric vs.				
Diesel	0.039	0.076	-0.029	0.634
CNG	0.011	0.038	-0.031	0.267
Old Diesel	0.891	1.199	0.032	10.318

Notes: Weighted by bus VMT from MOVES.

is positive) and relative to CNG is positive in a substantial minority of counties (the 57th percentile is positive). Relative to Old Diesel, the environmental benefit of electrification is substantial and positive in all counties emphasizing again the importance of replacing older diesel buses.

To understand these environmental benefits, Table 4 decomposes the air pollution damages from each bus into damages from CO_2, SO_2, and other local pollutants. Electric buses cause less damage from CO_2 than any other bus type, but they cause more damage from SO_2 than the non-electric buses. This is due to sulfur emissions from coal-fired power plants and the use of low sulfur diesel in both old and new diesel buses. Even though the electricity generation from coal-fired plants has decreased in recent years, they still generated about 30% of electricity in the U.S. in 2017.

Table 4: Decomposition of Air Pollution Damages ($ per mile)

	Total	CO_2	SO_2	other
Diesel	0.151	0.104	0.002	0.045
CNG	0.123	0.105	NA	0.017
Old Diesel	1.003	0.128	0.002	0.872
Electric	0.112	0.058	0.036	0.018

Notes: Mean damages weighted by bus VMT from MOVES.

Because bus use is concentrated in urban areas, we aggregate damages and environmental benefit to the MSA and analyze the total fleet of buses within the MSA. Table 5 shows damages at the MSA level based on estimated fleet bus miles from the MOVES model. The top twenty MSAs are ranked by the annual benefit, which is the difference between the damages from an all diesel fleet in the MSA and the damages from an all electric fleet. This benefit is highest in Los Angeles where air pollution damages from a new diesel bus fleet would be \$71.4 million per year, but the air pollution damages from a new electric bus fleet would be only \$6.4 million, which yields an annual benefit of \$65 million. This large benefit is driven by the large benefit per mile of \$0.634, which is the largest in the country. Other MSAs in the West also have large benefits per mile, e.g., Santa Ana, CA and San Diego, CA, and sixteen MSAs have benefits which exceed \$0.10 per mile.[15] Cities in the East tend to have a smaller benefit per mile but can still have substantial annual benefits. For example, Chicago, IL has a benefit of \$0.08 per mile and has an annual benefit of \$16 million from adopting an electric bus fleet relative to a new diesel fleet. For comparison, the table also reports damages from running the MSA's bus fleet entirely as old diesel buses and as new CNG buses. There are substantial damages from old diesel and hence substantial benefits from replacing pre-2010 buses. CNG buses are cleaner than Diesel in all MSAs, but, with the exception of Warren, MI, a fleet of CNG buses has higher damages than a fleet of electric buses for each MSA in Table 5.[16]

3 Net Present Value Benefit of Bus Electrification

In the previous section, we compared the air pollution damages from an electric bus and a forgone non-electric bus. The forgone bus, the bus which would have been purchased instead of the electric bus, would be determined by economic considerations: how much each bus costs to purchase and operate. Importantly, decision makers may or may not consider the external costs from air pollution in their decisions. To illustrate the cost calculations, we consider the investment decision for a new bus of each type. Because the bus types have different purchase costs and ongoing operating costs, we compare the net present value

[15] In addition to the MSAs in Table 5, this includes San Francisco, CA (\$0.12), Modesto, CA (\$0.12), Vallejo, CA (\$0.14), Santa Cruz, CA (\$0.12), Riverside, CA(\$0.12), Oakland, CA (\$0.16), Sacramento, CA (\$0.12), San Jose, CA (\$0.14), Stockton, CA (\$0.17).

[16] Table A in the Online Appendix shows a similar table for all 376 MSAs in the contiguous U.S.

Table 5: Damages and benefits by MSA

MSA	Old Diesel	CNG	Diesel	Electric	Annual Benefit	Benefit per mile	Bus VMT
Los Angeles, CA	1,064.0	33.8	71.4	6.4	65.0	0.634	102.5
New York, NY	426.4	21.4	33.8	16.7	17.1	0.127	135.1
Chicago, IL	424.2	28.6	41.5	25.5	16.0	0.080	200.2
Atlanta, GA	379.8	37.9	48.8	35.9	12.9	0.043	298.7
Newark, NJ	302.8	20.8	29.7	18.5	11.1	0.074	149.6
Phoenix, AZ	126.0	15.2	18.9	8.0	10.9	0.089	122.0
Riverside, CA	124.7	11.4	15.5	5.5	10.0	0.118	85.2
Santa Ana, CA	142.1	7.8	12.5	2.9	9.6	0.207	46.6
San Diego, CA	125.8	6.8	11.1	2.5	8.7	0.218	39.7
Dallas, TX	113.2	16.7	19.7	11.5	8.2	0.058	140.5
Edison, NJ	226.7	18.7	25.3	17.5	7.8	0.055	141.8
Washington, DC	212.8	21.4	27.4	20.7	6.7	0.039	169.8
Warren, MI	218.8	23.8	30.0	24.4	5.7	0.030	190.6
Detroit, MI	178.9	16.7	21.9	16.5	5.5	0.042	129.8
Oakland, CA	66.6	4.3	6.5	1.8	4.7	0.162	28.8
Houston, TX	62.8	9.9	11.5	7.0	4.5	0.054	84.3
Seattle, WA	49.2	6.3	7.7	3.4	4.3	0.083	52.0
Philadelphia, PA	114.9	8.3	11.6	7.5	4.1	0.068	60.4
Charlotte, NC	123.9	14.6	18.2	14.3	3.8	0.032	118.8
Sacramento, CA	47.3	4.4	5.8	2.1	3.8	0.115	32.6

Notes: Damages for “Old Diesel,” “CNG”, “Diesel” and “Electric” in millions of dollars per year. Annual Benefit is the difference between Diesel and Electric damages in millions of dollars. “Benefit per mile” is in dollars, and “Bus VMT” is bus vehicle miles traveled from MOVES in millions of miles per year.

(NPV) costs. Comparing these net present value costs gives the NPV benefit of an electric bus relative to the non-electric alternatives.

Consider investment in a new bus. Let $b \in \{d, c, e\}$ index the three bus types: diesel, CNG, and electric. The net present value NPV_{bi} for bus type b in location i is given by:[17]

$$NPV_{bi} = P_b + (Oper_{bi} + Ext_{bi}) \left(\frac{1}{r}\right) (1 - (1 + r)^{-\ell}) \tag{2}$$

where P_b is the initial purchase price of the bus, $Oper_{bi}$ is the annual operating costs, Ext_{bi} is annual externality cost, r is the discount rate, and ℓ is the operating lifetime of the bus. The annual operating cost, $Oper_{bi}$ depends on mileage, m, maintenance costs, c_b, and fuel costs which vary by location.[18] The externality cost, which also varies by location, is $\chi_{bi}m$ where χ_{bi} is the damage per mile in location i as calculated in Section 2.

The parameters for the net present value calculations are summarized in Table 6. For parameters that do not vary by location (not indexed by i), we use the mean value from different studies for our baseline calculations. In a sensitivity analysis, we analyze high and low values one standard error above and below the mean values. Electric buses are expected to have a purchase price premium above diesel of approximately $250,000. However, they are expected to be considerably cheaper to maintain, with an expected savings of 40 cents per mile. Relative to diesel, the purchase price premium of CNG buses is considerably smaller than that of electric buses. The expected lifetime of a bus, ℓ, is assumed to be 12 years with an expected usage, m, of 35,605 miles per year. The consumption of electricity for electric buses, e_i, varies by county due to the temperature correction. The prices of natural gas, electricity, and diesel fuels vary by state, and the values for these prices are equal to the average prices over the period from 2017-2019.

Using these parameters, Table 7 shows the summary statistics of evaluating (2) for each county. The table first breaks out the net present value into the purchase cost and the

[17] Calculations for the payback period are given in the Online Appendix.

[18] Annual fuel consumption for the diesel bus costs $f_{di}/d * m$ where f_{di} is diesel fuel cost in location i and d is MPGe. Annual fuel consumption for the CNG bus costs $f_{ci}/c * m * 143.94/1000 + 0.04m$ where f_{ci} is CNG cost in location i, c is MPGe, 143.94 is a conversion factor, and $0.04m$ is the cost of gas compression. Annual fuel consumption for the electric bus costs $f_{ei} * e_i * m$ where f_{ei} is electricity cost and e_i is the kWh per mile in location i.

Table 6: Summary Statistics of Parameters for NPV Calculations

Variable	Description	Mean	St. Dev.	N
m	Miles per year	35605	5244	5 studies
P_d	Purchase Price Diesel Bus (thousands dollars)	342.91	168.46	8 studies
P_c	Purchase Price CNG Bus (thousands of dollars)	374.60	See notes	
P_e	Purchase Price Electric Bus (thousands dollars)	604.55	244.94	8 studies
c_d	Maintenance Diesel (dollars per mile)	0.94	0.54	8 studies
c_c	Maintenance CNG (dollars per mile)	0.94	See notes	
c_e	Maintenance Electric (dollars per mile)	0.54	0.46	8 studies
ℓ	Expected Lifetime (years)	12	0.0	5 studies
r	Discount Rate	0.03	n.a.	1
d	Fuel Consumption Diesel (MPG)	4.68	n.a.	1
c	Fuel Consumption CNG (MPGe)	4.62	n.a.	1
e_i	Fuel Consumption Electric (kWh per mile)	2.32	0.06	3109 counties
χ_{di}	Damages Diesel (dollars per mile)	0.15	0.07	3109 counties
χ_{ci}	Damages CNG (dollars per mile)	0.12	0.03	3109 counties
χ_{ei}	Damages Electric (dollars per mile)	0.11	0.02	3109 counties
f_{di}	Fuel Cost Diesel (dollars per gallon)	2.56	0.19	48 states
f_{ci}	Fuel Cost CNG (dollars per thousand cf)	8.06	1.39	48 states
f_{ei}	Fuel Cost Electric (cents per kWh)	9.70	2.09	48 states

Notes: Miles per year from Protera (2018), Tong et al. (2018), Aber (2016), Cooney et al. (2013), and Lajunen and Lipman (2016). Electric and Diesel purchase prices calculated from Protera (2018), Tong et al. (2017), Aber (2016), Lajunen and Lipman (2016), Mahmoud et al. (2016), Noel and McCormack (2014), Raleigh News and Observer (2020), and Shirazi et al. (2015). Electric and Diesel maintenance costs calculated from Protera (2018), Tong et al. (2017), USDOT(2018), Aber (2016), Cooney et al. (2013), Mahmoud et al. (2016), Noel and McCormack (2016), and Shirazi et al (2015). Three studies, Tong et al. (2017), Lajunen and Lipmman (2016) and Shirazi et al. (2015), give data for CNG buses. All three assume the same maintenance costs for CNG as Diesel and the average purchase price premium for a CNG bus is $31,695. Expected lifetime from Protera (2018), Tong et al. (2018), USDOT(2018), Aber (2016), and Cooney et al. (2013). Diesel and CNG fuel consumption from Lowell (2013). Electric fuel consumption from Proterra with temperature correction. Diesel fuel costs from AAA (2020) and EIA(2020a); Electric fuel costs from EIA (2019) Table 5.6.A for commercial customers; and CNG fuel costs from EIA(2020b). All fuel costs are the average of monthly data from 2017-2019. See the Online Appendix for details of Diesel fuel costs including the treatment of tax exemptions.

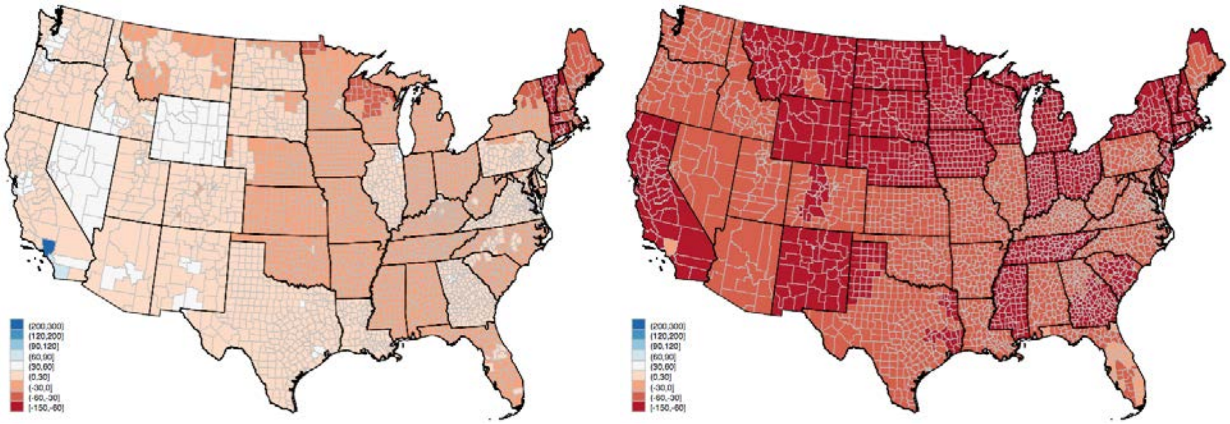
annual operating and damage costs and then presents the NPV at different interest rates. The top rows of the table show the results for the three different bus types and the bottom two rows show the NPV benefit of the Electric bus (i.e., the net present value reduction in costs from the electric bus) relative to the Diesel or CNG bus. Relative to Diesel, the table highlights the substantially higher purchase cost (about $250,000 higher) of the electric bus as well as the substantially lower operating and damage costs (about $25,000 lower per year). Because the upfront cost must be offset by gains over time, the NPV benefit of the Electric bus depends on the discount rate. At a high discount rate, the NPV benefit of the Electric bus is negative (indicating that the Diesel bus has lower overall costs) but at lower discount rates the NPV benefit of the Electric bus is positive. Relative to CNG, the Electric bus again has a higher purchase cost but lower operating costs. However, in this case the mean NPV benefit of the electric bus is never positive even at a very low discount rate. In fact, the NPV Benefit is negative in every county.

Table 7: Mean of NPV Calculations in Counties

		Annual	Annual		NPV	
	Purchase	Operating	Damages	r = 5%	r = 3%	r = 1%
Diesel	342.9	52.9	5.4	859.8	923.5	999.3
CNG	374.6	43.9	4.4	802.8	855.6	918.4
Electric	604.5	27.2	4.0	881.4	915.4	956.1
NPV Benefit of Electric Bus vs						
Diesel	-261.6	25.7	1.4	-21.5	8.0	43.3
CNG	-229.9	16.7	0.4	-78.5	-59.9	-37.6

Notes: Cost in thousands of dollars per bus. Weighted by bus VMT from MOVES.

The county-level NPV benefits of an Electric bus are illustrated in Figure 2a and 2b for $r = 0.03$. Relative to Diesel, the mean NPV benefit is $8,000. However the map in Figure 2a shows the distribution of this NPV benefit across counties. There are a substantial number of counties with large, positive NPV benefits. Due to the combination of large damages from diesel buses and the clean electricity grid, the NPV benefit is over $200,000 per bus in Los Angeles. However, there are also a substantial number of counties with negative NPV benefits, particularly in the upper Midwest and New England. This emphasizes the



(a) Relative to Diesel (b) Relative to CNG

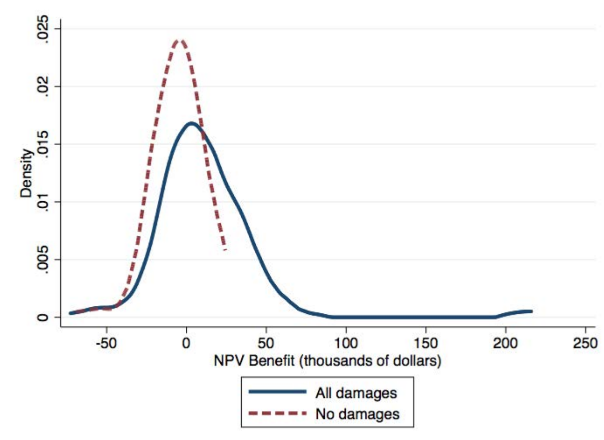
Figure 2: NPV Benefit of an Electric Bus by County (thousands of dollars)

significant spatial heterogeneity in the NPV benefit of the Electric bus relative to the Diesel bus.

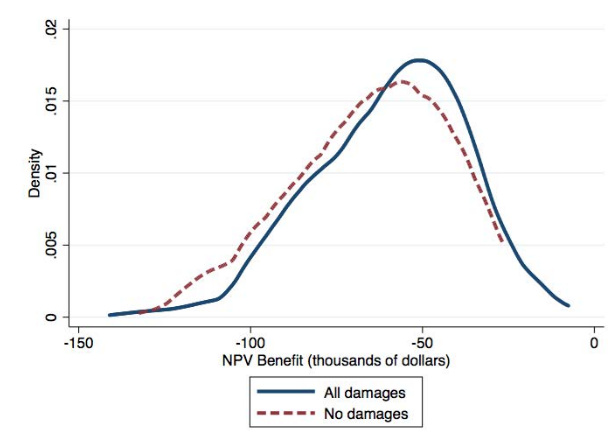
Relative to CNG, the mean NPV benefit of the Electric bus is negative (-$59,900). The map in Figure 2b shows heterogeneity in this NPV benefit but also shows that it is negative in each county. Although the Electric bus has a positive environmental benefit relative to the CNG bus and lower expected maintenance costs, the large upfront purchase price premium of the electric bus leads to the negative NPV benefit.

The types of transit buses we are considering are typically used in urban areas. So it is useful to trim the data shown in Figure 2a and 2b to exclude non-urban counties. A kernel density plot for the distribution of the NPV Benefit of the Electric bus relative to Diesel across urban counties is shown in the blue line in Figure 3a. The NPV Benefit is positive in about two thirds of urban counties. The distribution is skewed to the right because of a small number of counties, like Los Angeles, in which the NPV Benefit is very large. A similar plot for the distribution of the NPV Benefit relative to CNG is shown by the blue line in Figure 3b. The NPV Benefit is negative everywhere (i.e., CNG buses have lower costs in all urban counties) and the distribution is skewed to the left.

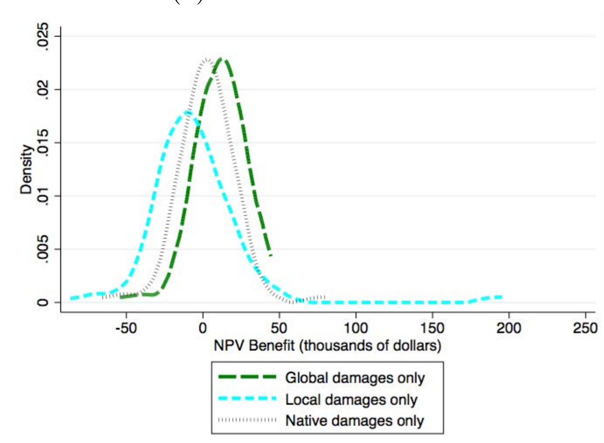
The NPV formula fully captures all of the costs to society, including the external costs due to damages from air pollution. However, decision makers may not fully incorporate all the relevant costs in their decisions. For example, the decision maker may ignore external costs or may include some external costs but ignore others. The effect on the NPV Benefit of



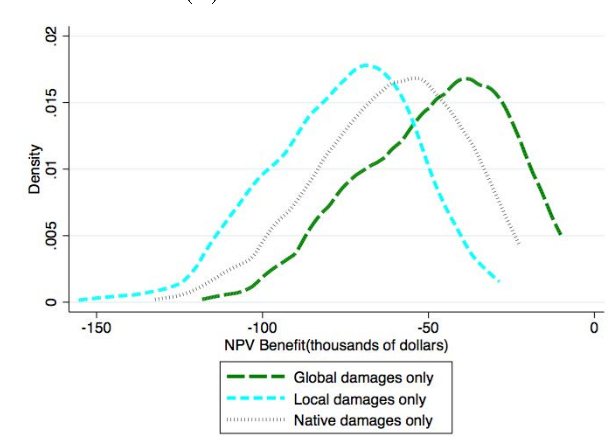
(a) Relative to Diesel



(b) Relative to CNG



(c) Relative to Diesel



(d) Relative to CNG

Figure 3: Distribution of NPV Benefit in Urban Counties

the Electric bus is not entirely obvious since ignoring external costs affects the costs of both the Electric bus and the alternative non-electric bus. To illustrate, we show kernel densities across urban counties of the NPV Benefit of the Electric bus when decision makers include or ignore some external costs.

The red dashed lines in Figure 3a and 3b show the kernel densities for the case where the decision maker ignores all external costs. Relative to Diesel, the distribution of NPV Benefit is positive in about one third of urban counties, and the distribution tightens considerably because the decision maker is ignoring the substantial environmental benefits in some urban counties, e.g., Los Angeles county. Relative to CNG, ignoring external costs shifts the density left, i.e., the NPV benefit is reduced by ignoring external costs. However, the shift is more modest since the environmental benefit is not as large especially on the right tail.

Figures 3c and 3d show the kernel densities for three additional NPV Benefit calculations, each reflecting a different perspective on the relevance of external costs to the decision maker. The green dashed line shows the NPV Benefit in which only the global damages from CO_2 are considered. Many popular discussions of the benefits of electrification only focus on these damages, ignoring the damages from local pollution. Relative to Diesel, accounting for only global damages leads to a NPV Benefit that has a narrower distribution because the right tail of benefits from local damages is ignored. Relative to CNG, accounting for only global damages does not shift the NPV Benefit substantially due to the lesser importance of local damages. Conversely, incorporating only local damages in the NPV calculation and ignoring global damages (the dashed teal lines) shifts the distribution to the left, such that the NPV Benefit relative to Diesel is negative in the majority of urban counties and the NPV Benefit relative to CNG is even more negative. Finally, our local damages include damages which may occur far from the source of the pollution. For example, our calculations of SO_2 damages include damages that occur in the county where the bus is driven as well as in all other counties to which the pollution is carried by air currents. Native damages are defined by Holland et al. (2016) as only those local damages that accrue to the county where the bus is driven. These damages may be the most politically relevant for a local decision maker. Accounting for only native damages (the dotted gray lines in Figures 3c and 3d) shows that the NPV Benefit relative to Diesel or CNG is higher than when only local damages are considered, but not as high as when only global damages only are considered. Overall, the NPV Benefits of bus electrification tend to be highest when including all damages from both local and global pollutants.

We conclude this section with a sensitivity analysis of the NPV Benefits. Seven parameters in Table 6 do not depend on location: the miles driven per year: m; the purchase price of the diesel, CNG, and electric buses: P_d, P_c and P_e; and the annual maintenance costs of the diesel, CNG, and electric buses: c_d, c_c, and c_e. For each of these parameters, we determine a high and low value (one standard error above and below the average value). The results of using the high and low values for each variable, keeping the other variables at baseline, are shown in Table 8. First consider the NPV Benefit of the Electric bus relative to Diesel in Panel A. Because the Electric bus has a higher purchase price but lower operating costs, the NPV Benefit shifts left or right depending on how the parameter affects the purchase price or operating costs. For example, higher annual miles, m, increases the NPV Benefit because the Electric bus has lower operating cost per mile. Similarly, lower electric bus maintenance costs or higher diesel bus maintenance costs increase the NPV Benefit because of the lower relative operating costs. On the other hand, a lower Electric bus purchase price or a higher Diesel bus purchase price increases the NPV Benefit by making the relative purchase price lower. Across the range of relevant parameters, favorable parameters can make the NPV Benefit positive for all counties, but even unfavorable parameters do not make the NPV Benefit negative for all counties.

Relative to CNG buses (Panel B), electric buses again have a purchase price disadvantage but a (smaller) operating costs advantage. Compared to the baseline mean NPV Benefit of -$59,900, higher annual miles, a higher CNG bus purchase price, a lower electric bus purchase price, higher CNG bus maintenance costs, and lower electric bus maintenance costs all increase (shift right) the NPV Benefit of an electric bus. Across the range of relevant parameters, favorable parameters can make the NPV Benefit positive in some counties and can make the mean NPV Benefit positive, but they do not make the NPV Benefit positive in all counties.

Up to now, we have assumed in the NPV calculations that marginal damages from electricity generation stay constant over the lifetime of the bus. But Holland et al. (2018)

document that marginal damages from electricity generation have decreased approximately five percent per year over the last decade in the East interconnection. Assuming that this rate of decline continues into the future in all interconnections gives the results in the last row of Panel A and B of Table 8. The Cleaner Future Grid gives a modest increase in the NPV Benefit of electric buses relative to both Diesel and CNG.

Table 8: Sensitivity Analysis of NPV Benefit of Bus Electrification

Panel A: NPV Benefit Relative to Diesel

	Mean	Std. Dev.	Min	Max
Baseline	8.0	32.0	-74.5	216.0
High Miles	25.8	34.1	-62.2	247.4
Low Miles	-9.7	29.9	-86.8	184.5
High Diesel Bus Price	67.6	32.0	-14.9	275.5
Low Diesel Bus Price	-51.5	32.0	-134.0	156.4
High Electric Bus Price	-78.6	32.0	-161.1	129.4
Low Electric Bus Price	94.6	32.0	12.1	302.6
High Diesel Maintenance	75.4	32.0	-7.1	283.3
Low Diesel Maintenance	-59.3	32.0	-141.8	148.6
High Electric Maintenance	-48.7	32.0	-131.2	159.2
Low Electric Maintenance	64.7	32.0	-17.8	272.7
Cleaner Future Grid	18.3	30.9	-62.2	221.7

Panel B: NPV Benefit Relative to CNG

	Mean	Std. Dev.	Min	Max
Baseline	-59.9	21.5	-143.2	-7.6
High Miles	-48.7	22.9	-137.5	7.1
Low Miles	-71.1	20.0	-148.9	-22.2
High CNG Bus Price	-0.3	21.5	-83.6	52.0
Low CNG Bus Price	-119.4	21.5	-202.8	-67.1
High Electric Bus Price	-146.5	21.5	-229.8	-94.2
Low Electric Bus Price	26.7	21.5	-56.6	79.0
High CNG Maintenance	7.5	21.5	-75.9	59.8
Low CNG Maintenance	-127.2	21.5	-210.5	-74.9
High Electric Maintenance	-116.6	21.5	-199.9	-64.3
Low Electric Maintenance	-3.2	21.5	-86.5	49.1
Cleaner Future Grid	-49.6	21.1	-130.9	-1.8

Notes: Values in thousands of dollars. Weighted by bus VMT from MOVES. High and low values are one standard error above and below average.

Taken as a whole, the results in this section show that there is considerable heterogeneity in the NPV benefit of the three types of buses. It is critical that decision makers evaluate local costs and environmental conditions when evaluating the lowest cost investment.

4 Conclusion and Policy Implications

Advances in electric motors, battery technology, wireless charging, and autonomous driving open new possibilities for electrification of transportation. Whether market forces can result in efficient electrification depends on the extent to which pollution can be adequately regulated. Understanding the benefits and costs of regulation is thus crucial to assessing public policy toward electrification.

Our location-specific calculations of the environmental benefits of bus electrification show positive benefits to electrification on average relative to each of the three alternatives. Relative to old diesel buses, which are quite dirty, the environmental benefit of electrification is positive everywhere and can be quite large. When compared to new diesel or CNG buses, the average of the per-mile benefit of an electric bus is $0.04 and $0.01, respectively. However, the average benefit masks significant spatial heterogeneity across counties. At one extreme, the electric buses produces $0.03 greater damage per mile than either a diesel or CNG bus. At the other extreme, the electric bus yields large benefits of $0.63 per mile, relative to a new diesel bus in Los Angeles. The environmental benefit of electrifying the entire bus fleet in Los Angeles (relative to a new diesel fleet) is $65 million per year. Other MSAs also have substantial environmental benefits from electrification relative to both diesel and CNG buses.

The value of an investment in an electric bus depends not just on the environmental benefit but also on the economic costs and benefits. Because electric buses are costlier to purchase but have lower operating and maintenance costs as well as lower environmental damages, we calculate the net present value (NPV) benefit of an electric bus, i.e., the present value of the reduced costs of purchasing and operating an electric bus over its lifetime. Relative to a diesel bus, the average NPV benefit of an electric bus is about $8000 per bus at a 3% discount rate. This NPV benefit is positive in most counties and is quite substantial in some counties (over $200,000 per bus in Los Angeles). This calculation provides strong support for bus electrification relative to diesel for much of the country.

What about CNG buses? While these buses are cleaner than diesel buses on average, they are dirtier than electric buses on average. On the other hand, their purchase price premium is considerably smaller than that of electric buses. According to our calculations, the NPV benefit of an electric bus relative to a CNG bus is negative in every county. This is evidence in support of CNG bus adoption. However, several caveats should be noted. First, conversion to an electric or CNG fleet requires substantial investment in either charging or refueling infrastructure. These costs are not modeled here. Second, as battery technology improves, the electric bus price premium is likely to decrease, and this can make the NPV benefit of electrification relative to CNG positive on average. Third, as electricity generation continues to de-carbonize it is possible that the future environmental benefit of the electric bus could increase more substantially than indicated by our sensitivity analysis of a changing grid. A dynamic investment model could better capture these considerations.

Urban bus systems rely on substantial public support. Ridership fares generally only cover a proportion of the costs of operating a municipal bus system and the remainder is primarily made up by a combination of local and federal support. This public support could be used to encourage adoption of cleaner bus alternatives, and our calculations illustrate where and what those alternatives are.

Appendix

AP3 Model Details

This paper uses the AP3 integrated assessment model (IAM), (see Clay et al., 2019; Holland et al., 2018 for recent applications) which is an updated version of the AP2 model (Muller, 2014; Jaramillo and Muller, 2016; Holland et al., 2016). The model links emissions of local air pollutants to concentrations, population exposure, physical health effects (premature mortality risk), and monetary damages.

The AP3 model begins by using the 2014 National Emissions Inventory (NEI) which is the most recent comprehensive inventory of air pollution emissions for the U.S. economy. AP3 matches reported emissions to the location of release. So-called area source emissions (vehicles, residences, and small businesses) are allocated to the county in which they are reported to have occurred. AP3 attributes point source emissions to facility location for nearly 700 large industrial emission sites (many of which are power stations). Discharges from other point sources are allocated to the county in which the NEI reports that they occurred.

A reduced complexity air quality model then links emissions to annual average concentrations. Crucially, for releases of nitrogen oxides (NO_X), sulfur dioxide (SO_2), ammonia (NH3), and volatile organic compounds (VOCs), AP3 models their contribution to ambient fine particulate matter ($PM_{2.5}$). AP3 also models the dispersion of primary (emitted) $PM_{2.5}$. Central to the formation of secondary PM2.5 are the processes associated with the nitrate-sulfate-ammonium equilibrium. While formation of ammonium sulfate is modeled in the same fashion as in AP2, AP3 employs a new regression-based approach to estimating the formation of ammonium nitrate from NO_X emissions. Specifically, in a series of offline regression analyses, a polynomial is fitted to the process linking nitrate, free ammonia, along with controls for temperature and humidity, to ambient ammonium nitrate (which is a constituent of PM2.5). The model is fit to daily predictions from the CAMx chemical transport model. The resulting fit of PM2.5 predicted by the AP3 model, by major species, is reported in Sergi et al., (2019).

Population and mortality rate data is gathered from the U.S. Census and the Centers for Disease Control and Prevention by age-group and county to estimate exposures in 2014. Then, peer-reviewed concentration-response functions linking exposure to changes in adult mortality rates are used to estimate the mortality risk consequences of emissions (Krewski et al., 2009; Lepeule et al., 2012). These studies comprise the most recent updates to the two most widely used epidemiological studies on the air pollution-mortality linkage in the policy analysis literature. Changes in mortality risk are valued using the Value of a Statistical Life (VSL) approach (Viscusi and Aldy, 2013). In this study, we employ the USEPA's preferred VSL of $7.4 million ($2006) which we inflate to year-2014 USD.

As in prior applications, AP3 is used to calculate the marginal ($/ton) damage from emissions of the five pollutants listed above. This computation is made by county (or source) of emission. The process of making this tabulation begins by running AP3 with baseline emissions (as reported by the USEPA in the 2014 NEI) to estimate associated baseline damages. Then, one (U.S. short) ton of emissions of a particular pollutant, perhaps NO_X, is added to reported emissions at a given site. AP3 is used to calculate the change in concentrations, exposure, physical health effects, and monetary damage. This change, of course, manifests across many locations receiving pollution. The total marginal damage is the spatial sum across receptor counties resulting from this additional emission of NO_X. Emissions at the chosen site are reset to baseline, and AP3 moves to the next source and repeats this calculation. This algorithm is repeated over all sources and pollutants. This process yields estimates of the ($/ton) marginal damage for all source locations and pollutants covered by AP3.

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Online Appendices

Age of Buses in the Fleet

From data in the National Transit Database (2018), we determined the age distribution of transit buses. There are 53,798 buses owned by entities in the database, and, of this total, 18491 are 10 years or older. The geographic distribution of these 10 years or older buses is shown in Figure A.[19] Large urban areas throughout the country have significant numbers of these old buses.

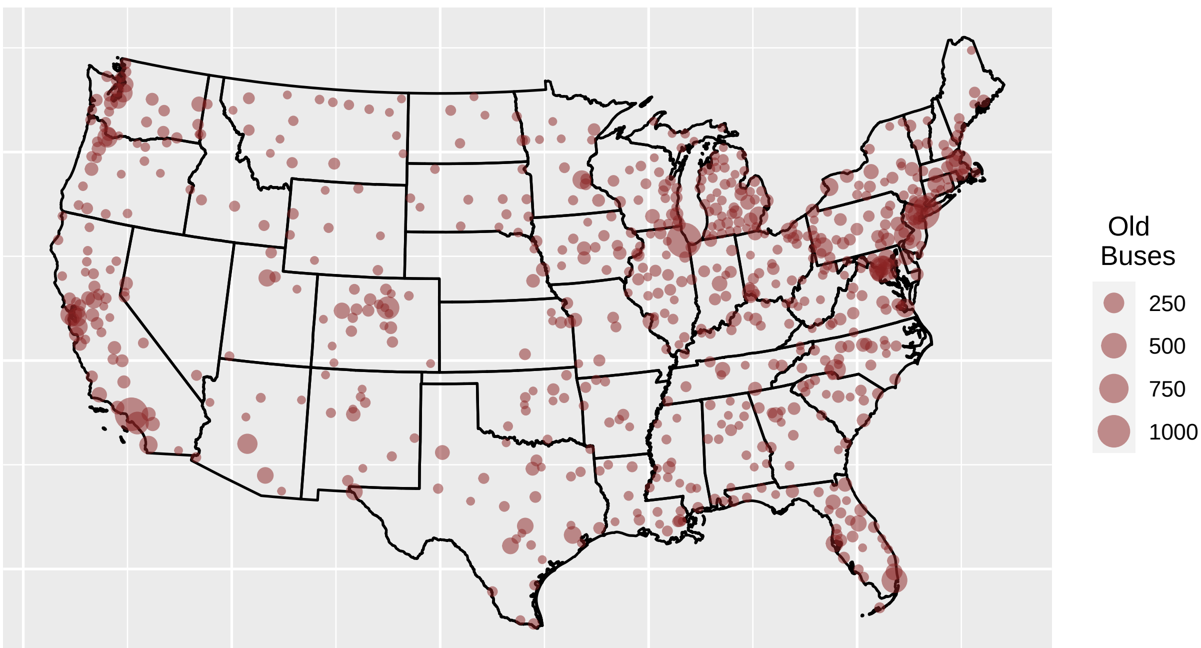

Figure A: Number of Buses 10 Years or Older

[19]The National Transit Database delineates buses by city name. We use data from `https://simplemaps.com/data/us-cities` to merge the city names into counties.

Diesel Fuel Costs

The Energy Information Administration (EIA 2020a) reports diesel fuel costs by PADD regions (New England, Central Atlantic, East Coast, Midwest, Gulf Coast, Rock Mountain, West Coast, California). The states that comprise a given region have the same color in Figure B. To determine diesel fuel costs, we first average the monthly prices in each PADD over 2017-2019. We then take 2019 average monthly state level prices from AAA (2020) and determine the state level premium above (or below) the average price within a PADD. The final diesel fuel cost in each state is equal to the average PADD price over 2017-2019 plus the state level premium minus a state diesel fuel tax exemption for government entities, if applicable.

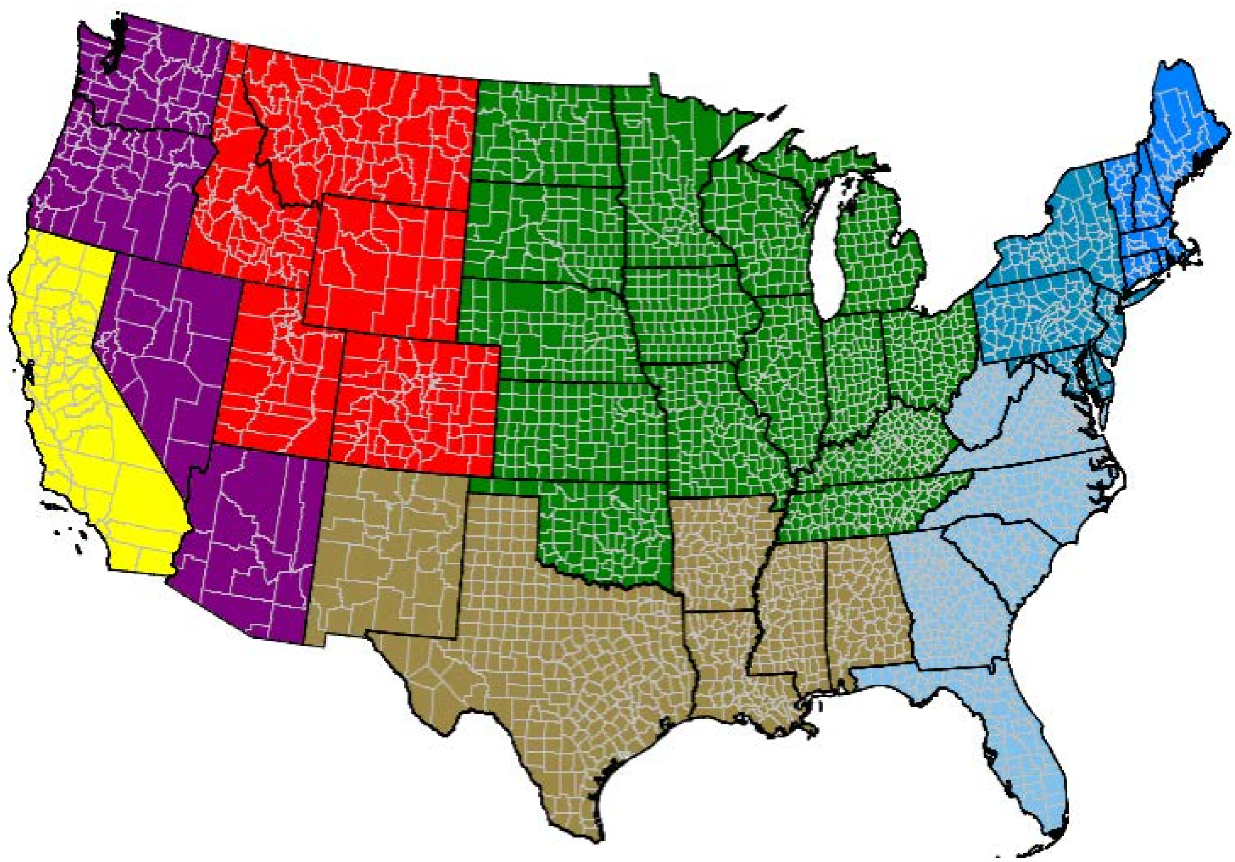

Figure B: PADD Regions

Environmental benefit of a fleet swap for all MSAs

In the main text we presented the annual benefit of a complete fleet swap from diesel buses to electric buses. Table A shows this information for all of the MSAs in the contiguous U.S. The environmental benefit is greater than one million dollars per year in about 50 MSAs. The "Old Diesel" column shows that a fleet of old Diesel buses leads to annual damages in excess of ten million dollars per year in a number of MSAs.

MSA	Old Diesel	CNG	Diesel	Electric	Annual Benefit	Benefit per mile	Bus VMT
Los Angeles, CA	1,064.0	33.8	71.4	6.4	65.0	0.634	102.5
New York, NY	426.4	21.4	33.8	16.7	17.1	0.127	135.1
Chicago, IL	424.2	28.6	41.5	25.5	16.0	0.080	200.2
Atlanta, GA	379.8	37.9	48.8	35.9	12.9	0.043	298.7
Newark, NJ	302.8	20.8	29.7	18.5	11.1	0.074	149.6
Phoenix, AZ	126.0	15.2	18.9	8.0	10.9	0.089	122.0
Riverside, CA	124.7	11.4	15.5	5.5	10.0	0.118	85.2
Santa Ana, CA	142.1	7.8	12.5	2.9	9.6	0.207	46.6
San Diego, CA	125.8	6.8	11.1	2.5	8.7	0.218	39.7
Dallas, TX	113.2	16.7	19.7	11.5	8.2	0.058	140.5
Edison, NJ	226.7	18.7	25.3	17.5	7.8	0.055	141.8
Washington, DC	212.8	21.4	27.4	20.7	6.7	0.039	169.8
Warren, MI	218.8	23.8	30.0	24.4	5.7	0.030	190.6
Detroit, MI	178.9	16.7	21.9	16.5	5.5	0.042	129.8
Oakland, CA	66.6	4.3	6.5	1.8	4.7	0.162	28.8
Houston, TX	62.8	9.9	11.5	7.0	4.5	0.054	84.3
Seattle, WA	49.2	6.3	7.7	3.4	4.3	0.083	52.0
Philadelphia, PA	114.9	8.3	11.6	7.5	4.1	0.068	60.4
Charlotte, NC	123.9	14.6	18.2	14.3	3.8	0.032	118.8
Sacramento, CA	47.3	4.4	5.8	2.1	3.8	0.115	32.6
Fort Worth, TX	50.5	7.9	9.2	5.5	3.7	0.055	67.1
San Jose, CA	47.6	3.6	5.1	1.6	3.5	0.142	24.9
Denver, CO	33.1	4.5	5.3	2.4	2.9	0.080	37.0
Camden, NJ	86.3	7.6	10.1	7.2	2.9	0.049	58.8
Minneapolis-St. Paul, MN	113.7	11.3	14.6	11.8	2.9	0.033	88.0
Baltimore-Towson, MD	91.5	9.6	12.2	9.4	2.8	0.036	76.5
Portland, OR	23.0	5.1	5.6	2.9	2.8	0.061	45.5
Raleigh-Cary, NC	86.8	11.3	13.8	11.2	2.6	0.028	92.9
Cincinnati-Middletown, OH-KY-IN	78.4	7.6	9.9	7.4	2.6	0.043	59.8
Pittsburgh, PA	73.6	7.2	9.4	7.0	2.4	0.043	56.0
Tampa, FL	61.1	5.5	7.4	5.1	2.2	0.052	42.5
Stockton, CA	30.9	2.0	3.1	0.9	2.2	0.166	13.3
San Francisco,CA	27.4	2.3	3.2	1.1	2.1	0.121	17.4
Salt Lake City, UT	24.5	3.0	3.7	1.7	2.1	0.083	24.9
Las Vegas, NV	17.6	3.1	3.5	1.7	1.8	0.070	26.2
Cleveland-Elyria-Mentor, OH	59.9	6.1	7.8	6.1	1.7	0.036	48.5
San Antonio, TX	20.9	4.4	4.8	3.1	1.7	0.045	38.4
Columbus, OH	59.1	7.0	8.7	7.1	1.6	0.029	56.9
Orlando, FL	49.9	5.4	6.8	5.2	1.6	0.037	43.0
St. Louis, MO-IL	83.2	12.9	15.1	13.5	1.6	0.014	109.3
Wilmington, DE-MD-NJ	59.0	7.3	8.9	7.3	1.5	0.026	59.8
Bakersfield, CA	15.8	2.3	2.7	1.2	1.5	0.081	18.7
Nassau-Suffolk, NY	39.3	2.8	3.9	2.5	1.4	0.072	19.9
Fresno, CA	13.2	1.8	2.2	0.9	1.3	0.086	14.8
Austin-Round Rock, TX	15.7	3.0	3.3	2.1	1.2	0.049	25.7

Richmond, VA	58.5	9.3	10.8	9.6	1.2	0.016	79.2
Albuquerque, NM	11.0	2.2	2.5	1.2	1.2	0.065	19.0
Oxnard-Thousand Oaks-Ventura, CA	13.2	1.5	1.9	0.7	1.2	0.098	11.9
Greensboro-High Point, NC	38.5	4.8	5.9	4.7	1.2	0.030	39.0
Indianapolis, IN	42.8	5.2	6.4	5.2	1.1	0.027	42.1
Modesto, CA	13.2	1.2	1.6	0.6	1.1	0.119	8.9
Bethesda-Frederick-Gaithersburg, MD	34.2	3.6	4.6	3.5	1.0	0.036	28.9
Dayton, OH	34.4	3.8	4.7	3.7	1.0	0.034	30.0
Ft Lauderdale, FL	29.1	3.0	3.9	2.9	1.0	0.041	24.0
Vallejo-Fairfield, CA	12.5	0.9	1.3	0.4	0.9	0.138	6.7
Tacoma, WA	7.9	1.7	1.9	1.0	0.9	0.061	14.9
Louisville, KY-IN	30.6	3.5	4.4	3.5	0.9	0.032	28.3
Tucson, AZ	7.6	1.6	1.8	0.9	0.9	0.063	14.2
Akron, OH	29.5	3.1	3.9	3.1	0.9	0.035	24.5
Boise City-Nampa, ID	7.4	1.6	1.8	0.9	0.9	0.060	14.3
Flagstaff, AZ	5.3	1.5	1.6	0.9	0.7	0.056	13.5
Durham, NC	32.5	5.1	6.0	5.3	0.7	0.017	43.5
Allentown-Bethlehem-Easton, PA-NJ	29.6	3.7	4.5	3.8	0.7	0.024	30.7
El Paso, TX	6.6	1.1	1.3	0.6	0.7	0.071	9.7
Provo-Orem, UT	5.5	1.3	1.4	0.8	0.7	0.057	11.5
Santa Rosa-Petaluma, CA	7.1	0.9	1.1	0.4	0.6	0.094	6.9
Reno-Sparks, NV	4.6	1.3	1.4	0.8	0.6	0.054	11.7
Salem, OR	5.2	1.1	1.3	0.6	0.6	0.062	10.1
Las Cruces, NM	4.9	1.1	1.2	0.6	0.6	0.063	9.3
Virginia Beach-Norfolk-Newport News, VA	38.1	7.2	8.2	7.6	0.6	0.009	63.2
Trenton-Ewing, NJ	20.0	2.2	2.8	2.2	0.6	0.032	17.7
Atlan City, NJ	25.1	3.6	4.3	3.7	0.6	0.019	30.2
Kansas City, MO-KS	41.2	6.8	7.8	7.3	0.6	0.010	58.6
Miami, FL	24.6	3.7	4.3	3.8	0.6	0.018	31.2
Winston-Salem, NC	21.2	3.1	3.7	3.2	0.5	0.020	26.1
Colorado Springs, CO	4.3	0.9	1.0	0.5	0.5	0.061	8.2
Nashville-Davidson–Murfreesboro, TN	26.9	4.6	5.3	4.8	0.5	0.013	39.6
Lake County-Kenosha County, IL-WI	25.6	3.3	4.0	3.5	0.5	0.018	27.7
Fayetteville, NC	18.8	2.8	3.3	2.8	0.5	0.021	23.5
Milwaukee-Waukesha-West Allis, WI	27.7	3.5	4.3	3.8	0.5	0.017	29.2
Visalia-Porterville, CA	3.9	0.8	0.9	0.5	0.5	0.065	7.2
Merced, CA	5.0	0.6	0.8	0.3	0.5	0.089	5.2
Canton-Massillon, OH	14.4	1.5	1.9	1.5	0.4	0.036	12.0
Prescott, AZ	3.0	0.9	0.9	0.5	0.4	0.057	7.7
Salinas, CA	3.3	0.8	0.9	0.4	0.4	0.062	7.0
Santa Barbara-Santa Maria-Goleta, CA	4.2	0.6	0.8	0.3	0.4	0.082	5.3
Eugene-Springfield, OR	2.2	1.0	1.0	0.6	0.4	0.047	9.0
Spokane, WA	2.8	0.9	1.0	0.6	0.4	0.050	8.4
Hickory-Lenoir-Morganton, NC	17.6	2.7	3.2	2.8	0.4	0.018	23.1
West Palm Beach, FL	16.5	2.4	2.8	2.4	0.4	0.020	20.1
Killeen-Temple-Fort Hood, TX	4.6	1.0	1.1	0.7	0.4	0.043	9.0
Ann Arbor, MI	24.5	3.7	4.3	3.9	0.4	0.013	30.9
Deltona, FL	10.8	1.1	1.4	1.0	0.4	0.046	8.3
Greenville, SC	13.5	1.8	2.2	1.8	0.4	0.026	14.8
Ogden-Clearfield, UT	3.1	0.7	0.8	0.4	0.4	0.056	6.7
El Centro, CA	2.9	0.8	0.8	0.5	0.4	0.055	6.8
Santa Cruz-Watsonville, CA	4.8	0.4	0.6	0.2	0.4	0.116	3.2
Youngstown-Warren-Boardman, OH-PA	16.5	2.2	2.7	2.3	0.4	0.020	18.5
Asheville, NC	18.7	3.2	3.7	3.3	0.4	0.013	27.7
Knoxville, TN	16.2	2.6	3.0	2.7	0.4	0.016	22.0
Birmingham-Hoover, AL	21.7	4.1	4.7	4.3	0.4	0.010	35.7
Flint, MI	31.4	5.1	5.9	5.5	0.4	0.008	43.2
Greeley, CO	3.1	0.6	0.7	0.3	0.3	0.064	5.3
Cambridge-Newton-Framingham, MA	12.6	1.4	1.7	1.4	0.3	0.031	10.9

San Luis Obispo-Paso Robles, CA	2.9	0.5	0.6	0.3	0.3	0.071	4.7
Jacksonville, FL	19.3	3.5	4.0	3.6	0.3	0.011	30.3
Toledo, OH	17.8	2.6	3.1	2.7	0.3	0.015	21.7
Dover, DE	20.6	3.7	4.2	3.9	0.3	0.010	31.7
Sarasota, FL	11.8	1.6	1.9	1.6	0.3	0.024	13.2
Farmington, NM	2.1	0.6	0.7	0.4	0.3	0.053	5.8
Coeur d'Alene, ID	2.3	0.6	0.7	0.4	0.3	0.053	5.8
Olympia, WA	2.0	0.6	0.7	0.4	0.3	0.053	5.7
McAllen-Edinburg-Pharr, TX	3.3	1.0	1.0	0.7	0.3	0.035	8.6
Madera, CA	2.7	0.5	0.5	0.3	0.3	0.072	4.1
Santa Fe, NM	2.1	0.6	0.6	0.3	0.3	0.056	5.1
Hanford-Corcoran, CA	2.9	0.4	0.5	0.2	0.3	0.080	3.5
Memphis, TN-MS-AR	16.9	3.0	3.5	3.2	0.3	0.010	26.4
Medford, OR	1.4	0.6	0.6	0.3	0.3	0.048	5.3
Kennewick-Richland-Pasco, WA	1.5	0.6	0.6	0.3	0.3	0.048	5.3
Corpus Christi, TX	2.6	0.8	0.8	0.6	0.3	0.036	7.0
Reading, PA	9.4	1.1	1.4	1.2	0.3	0.027	9.4
Fort Collins-Loveland, CO	2.0	0.5	0.5	0.3	0.2	0.055	4.4
Waco, TX	2.8	0.6	0.7	0.5	0.2	0.043	5.6
Worcester, MA	8.4	0.9	1.2	0.9	0.2	0.033	7.3
Chattanooga, TN-GA	11.8	2.0	2.3	2.1	0.2	0.014	17.5
Vineland-Millville-Bridgeton, NJ at	12.6	2.1	2.4	2.2	0.2	0.013	17.7
Idaho Falls, ID	1.9	0.5	0.5	0.3	0.2	0.054	4.3
Redding, CA	1.2	0.5	0.5	0.3	0.2	0.049	4.7
Monroe, MI	12.6	1.8	2.2	2.0	0.2	0.015	15.4
York-Hanover, PA	8.1	1.0	1.2	1.0	0.2	0.029	7.9
Lansing-East Lansing, MI	27.2	4.8	5.5	5.3	0.2	0.005	41.1
Yuma, AZ	1.5	0.5	0.5	0.3	0.2	0.052	4.2
Bremerton-Silverdale, WA	1.5	0.4	0.5	0.3	0.2	0.053	4.1
Spartanburg, SC	7.4	1.0	1.2	1.0	0.2	0.026	8.2
Lancaster, PA	7.1	0.8	1.0	0.8	0.2	0.031	6.7
Tyler, TX	2.4	0.5	0.6	0.4	0.2	0.045	4.5
Hagerstown-Martinsburg, MD-WV	11.3	1.8	2.1	1.9	0.2	0.013	15.4
Yakima, WA	1.1	0.5	0.5	0.3	0.2	0.045	4.5
Hartford-West Hartford-East Hartford, C	11.1	1.6	1.9	1.7	0.2	0.014	13.7
Gary, IN ivision	12.1	1.8	2.2	2.0	0.2	0.012	15.6
Ocala, FL	7.2	1.0	1.2	1.0	0.2	0.022	8.6
Roanoke, VA	9.9	1.7	1.9	1.7	0.2	0.013	14.2
Longview, WA	1.5	0.4	0.4	0.2	0.2	0.059	3.2
St. George, UT	1.1	0.4	0.4	0.2	0.2	0.050	3.8
Bridgeport-Stamford-Norwalk, CT	7.6	0.9	1.1	0.9	0.2	0.025	7.6
Brownsville-Harlingen, TX	1.9	0.6	0.6	0.4	0.2	0.036	5.1
Yuba City, CA	1.5	0.3	0.4	0.2	0.2	0.062	3.0
Palm Bay, FL	7.7	1.2	1.4	1.2	0.2	0.018	9.9
Augusta-Richmond County, GA-SC	11.6	2.2	2.5	2.4	0.2	0.009	19.6
Boulder, CO	1.4	0.3	0.4	0.2	0.2	0.060	2.8
Columbia, SC	13.0	2.6	2.9	2.8	0.2	0.007	22.8
Cape Coral, FL	7.6	1.2	1.4	1.2	0.2	0.017	10.0
Chico, CA	1.1	0.3	0.4	0.2	0.2	0.055	3.1
Pueblo, CO	1.4	0.3	0.3	0.2	0.2	0.061	2.8
Boston-Quincy, MA	10.0	1.5	1.7	1.5	0.2	0.013	12.3
Bend, OR	0.8	0.4	0.4	0.2	0.2	0.044	3.7
Mount Vernon-Anacortes, WA a	1.0	0.4	0.4	0.2	0.2	0.046	3.5
Bellingham, WA	0.7	0.4	0.4	0.3	0.2	0.041	3.8
Abilene, TX	1.5	0.5	0.5	0.4	0.2	0.035	4.4
Napa, CA	1.7	0.2	0.2	0.1	0.1	0.099	1.5
New Orleans-Metairie-Kenner, LA	12.7	2.6	2.9	2.7	0.1	0.006	22.8
Poughkeepsie-Newburgh-Middletown, NY	7.9	1.2	1.4	1.3	0.1	0.014	10.1
Billings, MT	1.0	0.3	0.3	0.2	0.1	0.050	2.8

Oklahoma City, OK	21.2	4.4	4.8	4.7	0.1	0.004	38.3
Harrisburg-Carlisle, PA	8.5	1.4	1.6	1.5	0.1	0.011	11.9
Gainesville, GA	5.5	0.8	1.0	0.8	0.1	0.020	6.9
Pocatello, ID	0.9	0.3	0.3	0.2	0.1	0.048	2.8
Providence-New Bedford-Fall River, RI-M	9.4	1.5	1.7	1.6	0.1	0.011	12.5
Anderson, SC	4.8	0.6	0.8	0.6	0.1	0.025	5.4
Grand Rapids-Wyoming, MI	16.9	3.0	3.4	3.3	0.1	0.005	25.6
Lakeland, FL	8.5	1.6	1.8	1.7	0.1	0.010	13.6
Fort Wayne, IN	7.2	1.1	1.3	1.2	0.1	0.014	9.4
Lynchburg, VA	7.1	1.3	1.4	1.3	0.1	0.012	10.8
Midland, TX	1.3	0.4	0.4	0.3	0.1	0.037	3.3
Rocky Mount, NC	7.4	1.4	1.6	1.5	0.1	0.009	12.3
Springfield, OH	5.0	0.7	0.8	0.7	0.1	0.021	5.5
Jackson, MI	9.4	1.5	1.8	1.7	0.1	0.009	13.2
Burlington, NC	5.8	1.0	1.1	1.0	0.1	0.013	8.5
Grand Junction, CO	0.8	0.2	0.3	0.1	0.1	0.053	2.1
Charleston, WV	6.8	1.2	1.4	1.3	0.1	0.010	10.8
Tulsa, OK	14.5	3.0	3.3	3.2	0.1	0.004	26.0
Wenatchee, WA	0.7	0.3	0.3	0.2	0.1	0.046	2.4
Lexington-Fayette, KY	5.4	0.9	1.0	0.9	0.1	0.014	7.5
Cheyenne, WY	0.7	0.2	0.2	0.1	0.1	0.052	2.1
Kingsport-Bristol-Bristol, TN-VA	5.8	1.0	1.2	1.1	0.1	0.012	8.8
New Haven-Milford, CT	6.4	1.0	1.1	1.0	0.1	0.013	8.3
Scranton–Wilkes-Barre, PA	8.3	1.4	1.6	1.5	0.1	0.009	11.7
Baton Rouge, LA	12.3	2.6	2.9	2.8	0.1	0.004	23.3
Wichita Falls, TX	1.1	0.3	0.3	0.2	0.1	0.037	2.7
Huntsville, AL	5.9	1.1	1.3	1.2	0.1	0.010	9.7
Ocean City, NJ	7.7	1.5	1.6	1.5	0.1	0.008	12.7
Odessa, TX	1.0	0.3	0.3	0.2	0.1	0.036	2.6
Macon, GA	9.6	2.0	2.3	2.2	0.1	0.005	18.0
Missoula, MT	0.6	0.2	0.2	0.1	0.1	0.047	2.0
Wilmington, NC	10.6	2.5	2.7	2.6	0.1	0.004	21.9
Sherman-Denison, TX	1.0	0.3	0.3	0.2	0.1	0.041	2.3
Battle Creek, MI	13.5	2.5	2.8	2.7	0.1	0.004	21.4
Victoria, TX	0.8	0.3	0.3	0.2	0.1	0.033	2.7
Dalton, GA	4.7	0.8	1.0	0.9	0.1	0.012	7.3
Lewiston, ID-WA	0.5	0.2	0.2	0.1	0.1	0.047	1.8
Shreveport-Bossier City, LA	8.9	1.9	2.1	2.0	0.1	0.005	16.6
Corvallis, OR	0.5	0.2	0.2	0.1	0.1	0.050	1.6
Mobile, AL	5.8	1.2	1.3	1.2	0.1	0.008	10.3
Goldsboro, NC	4.2	0.8	0.9	0.8	0.1	0.012	6.5
Laredo, TX	0.6	0.3	0.3	0.2	0.1	0.026	3.0
Anderson, IN	3.2	0.4	0.5	0.4	0.1	0.021	3.6
San Angelo, TX	0.7	0.2	0.2	0.2	0.1	0.035	2.1
Punta Gorda, FL	2.8	0.4	0.5	0.4	0.1	0.023	3.1
Pensacola-Ferry Pass-Brent, FL	6.0	1.2	1.4	1.3	0.1	0.007	11.0
Danville, VA	3.1	0.5	0.6	0.5	0.1	0.017	4.2
Lebanon, PA	3.4	0.5	0.6	0.5	0.1	0.017	4.0
Rapid City, SD	0.6	0.2	0.2	0.2	0.1	0.033	2.1
Huntington-Ashland, WV-KY-OH	4.4	0.8	0.9	0.9	0.1	0.010	7.1
Niles-Benton Harbor, MI	13.0	2.5	2.9	2.8	0.1	0.003	22.1
Casper, WY	0.5	0.1	0.1	0.1	0.1	0.054	1.2
Logan, UT-ID	0.5	0.1	0.2	0.1	0.1	0.050	1.3
Kalamazoo-Portage, MI	14.6	2.8	3.2	3.1	0.1	0.003	24.5
Manchester-Nashua, NH	15.1	2.8	3.2	3.1	0.1	0.003	24.4
Little Rock-North Little Rock, AR	9.0	2.0	2.2	2.2	0.1	0.003	17.9
Tuscaloosa, AL	4.5	0.9	1.0	1.0	0.1	0.007	7.9
Port St. Lucie, FL	4.9	1.0	1.1	1.0	0.1	0.007	8.7
Great Falls, MT	0.4	0.1	0.1	0.1	0.1	0.048	1.2

Mansfield, OH	3.4	0.5	0.6	0.6	0.1	0.013	4.6
Athens-Clarke County, GA	4.0	0.8	0.9	0.8	0.1	0.008	6.9
Wheeling, WV-OH	3.3	0.6	0.6	0.6	0.1	0.011	4.8
Rockford, IL	8.3	1.5	1.7	1.6	0.1	0.004	12.6
Rockingham County, NH	14.3	2.7	3.1	3.0	0.1	0.002	23.7
Columbus, GA-AL	5.6	1.2	1.4	1.3	0.1	0.005	10.8
Weirton-Steubenville, WV-OH	2.4	0.3	0.4	0.4	0.0	0.017	2.9
Kankakee-Bradley, IL	3.2	0.5	0.6	0.5	0.0	0.012	4.2
Carson City, NV	0.4	0.1	0.1	0.0	0.0	0.061	0.8
Johnstown, PA	2.9	0.5	0.5	0.5	0.0	0.011	4.0
South Bend-Mishawaka, IN-MI	4.4	0.8	0.9	0.8	0.0	0.007	6.7
Rome, GA	2.3	0.4	0.5	0.4	0.0	0.013	3.5
Salisbury, MD	4.3	0.9	1.0	1.0	0.0	0.005	8.1
Blacksburg-Christiansburg-Radford, VA	5.0	1.1	1.2	1.2	0.0	0.005	9.5
Morristown, TN	2.5	0.5	0.5	0.5	0.0	0.011	4.0
Muncie, IN	2.2	0.3	0.4	0.3	0.0	0.015	2.8
Johnson City, TN	2.4	0.4	0.5	0.5	0.0	0.011	3.7
Parkersburg-Marietta, WV-OH	3.1	0.6	0.7	0.6	0.0	0.008	5.0
Lima, OH	2.7	0.4	0.5	0.5	0.0	0.011	3.8
Charleston-North Charleston, SC	7.5	1.8	2.0	2.0	0.0	0.002	16.5
Michigan City-La Porte, IN	3.1	0.5	0.6	0.5	0.0	0.009	4.3
Evansville, IN-KY	4.9	1.0	1.1	1.1	0.0	0.004	9.0
Myrtle Beach-Conway-North Myrtle Beach,	3.7	0.8	0.9	0.9	0.0	0.005	7.5
Buffalo-Niagara Falls, NY	8.1	1.5	1.7	1.7	0.0	0.003	13.0
Racine, WI	2.8	0.4	0.5	0.5	0.0	0.009	3.6
Janesville, WI	3.0	0.5	0.6	0.5	0.0	0.008	4.1
Decatur, AL	2.7	0.5	0.6	0.6	0.0	0.007	4.8
Charlottesville, VA	5.3	1.2	1.3	1.3	0.0	0.003	10.7
Winchester, VA-WV	3.4	0.7	0.8	0.7	0.0	0.005	6.0
Norwich-New London, CT	2.4	0.4	0.5	0.4	0.0	0.009	3.5
Madison, WI	10.3	1.9	2.2	2.1	0.0	0.002	16.5
Harrisonburg, VA	3.1	0.7	0.7	0.7	0.0	0.005	5.8
Holland-Grand Haven, MI	4.8	0.9	1.0	1.0	0.0	0.004	7.7
Columbus, IN	1.5	0.3	0.3	0.3	0.0	0.012	2.2
Morgantown, WV	2.3	0.4	0.5	0.5	0.0	0.007	3.8
Peoria, IL	8.8	1.8	2.0	2.0	0.0	0.002	15.9
Bloomington, IN	2.1	0.4	0.5	0.4	0.0	0.007	3.6
Anniston-Oxford, AL	1.9	0.4	0.4	0.4	0.0	0.007	3.4
Gadsden, AL	1.9	0.4	0.4	0.4	0.0	0.007	3.4
Cleveland, TN	1.7	0.4	0.4	0.4	0.0	0.007	3.1
Altoona, PA	1.4	0.2	0.3	0.2	0.0	0.012	1.9
Springfield, MA	4.0	0.7	0.8	0.8	0.0	0.003	6.5
Florence, SC	2.9	0.7	0.7	0.7	0.0	0.004	5.9
Essex County, MA	3.6	0.7	0.7	0.7	0.0	0.003	5.8
Springfield, IL	4.5	1.0	1.1	1.0	0.0	0.002	8.4
Longview, TX	2.5	0.5	0.6	0.6	0.0	0.004	4.8
Sandusky, OH	2.4	0.5	0.5	0.5	0.0	0.005	3.9
Saginaw-Saginaw Township North, MI	4.2	0.8	0.9	0.9	0.0	0.003	6.8
Greenville, NC	4.4	1.1	1.2	1.2	0.0	0.002	9.8
Kokomo, IN	1.2	0.2	0.2	0.2	0.0	0.010	1.8
Jackson, MS	6.7	1.7	1.8	1.8	0.0	0.001	14.8
Elizabethtown, KY	1.6	0.3	0.4	0.4	0.0	0.006	2.9
Muskegon-Norton Shores, MI a	5.4	1.0	1.2	1.2	0.0	0.002	9.0
Elkhart-Goshen, IN	2.4	0.4	0.5	0.5	0.0	0.004	3.9
Florence-Muscle Shoals, AL	1.9	0.4	0.5	0.5	0.0	0.004	3.9
Bowling Green, KY	1.6	0.3	0.4	0.4	0.0	0.005	3.0
State College, PA	2.6	0.5	0.6	0.6	0.0	0.003	4.6
Clarksville, TN-KY	2.5	0.6	0.6	0.6	0.0	0.003	5.1
Cumberland, MD-WV	3.0	0.6	0.7	0.7	0.0	0.002	5.7

Champaign-Urbana, IL	4.2	0.9	1.0	1.0	0.0	0.001	7.9
Lafayette, IN	2.0	0.4	0.5	0.5	0.0	0.002	3.7
Danville, IL	1.9	0.4	0.4	0.4	0.0	0.002	3.5
Davenport-Moline-Rock Island, IA-IL	5.7	1.2	1.3	1.3	0.0	0.001	10.2
Kingston, NY	2.2	0.4	0.5	0.5	0.0	0.002	3.9
Warner Robins, GA	2.5	0.6	0.7	0.7	0.0	0.001	5.5
Terre Haute, IN	2.1	0.5	0.5	0.5	0.0	0.001	4.2
Sumter, SC	1.2	0.3	0.3	0.3	0.0	0.002	2.6
Savannah, GA	7.0	1.8	2.0	1.9	0.0	0.000	16.2
Gainesville, FL	3.0	0.8	0.8	0.8	0.0	0.001	6.8
Auburn-Opelika, AL	1.6	0.4	0.5	0.4	0.0	0.001	3.7
Decatur, IL	2.3	0.5	0.6	0.5	0.0	0.001	4.4
Owensboro, KY	1.0	0.2	0.3	0.3	0.0	0.002	2.1
Bloomington-Normal, IL	3.3	0.7	0.8	0.8	0.0	0.000	6.3
Jackson, TN	1.6	0.4	0.4	0.4	0.0	0.001	3.6
Hot Springs, AR	0.6	0.2	0.2	0.2	0.0	0.001	1.4
Naples, FL	2.9	0.7	0.8	0.8	0.0	0.000	6.4
Jonesboro, AR	1.0	0.2	0.3	0.3	0.0	0.000	2.2
Texarkana, TX-Texarkana, AR	2.1	0.5	0.6	0.6	0.0	0.000	4.8
Vero Beach, FL	0.9	0.2	0.3	0.3	-0.0	-0.000	2.1
Williamsport, PA	1.4	0.3	0.4	0.4	-0.0	-0.001	2.8
Pascagoula, MS	2.6	0.7	0.7	0.7	-0.0	-0.000	6.2
Houma-Bayou Cane-Thibodaux, LA	1.5	0.4	0.4	0.4	-0.0	-0.001	3.7
Beaumont-Port Arthur, TX	4.3	1.1	1.2	1.2	-0.0	-0.000	10.0
Lafayette, LA	3.2	0.8	0.9	0.9	-0.0	-0.000	7.5
College Station-Bryan, TX	2.0	0.5	0.5	0.5	-0.0	-0.001	4.5
Lawrence, KS	0.4	0.1	0.1	0.1	-0.0	-0.004	1.0
Fayetteville-Springdale-Rogers, AR-MO	4.0	1.0	1.1	1.1	-0.0	-0.000	9.3
Pittsfield, MA	0.9	0.2	0.2	0.2	-0.0	-0.003	1.8
Montgomery, AL	4.9	1.3	1.4	1.4	-0.0	-0.000	11.7
Pine Bluff, AR	0.9	0.3	0.3	0.3	-0.0	-0.002	2.4
Fond du Lac, WI	1.3	0.3	0.3	0.3	-0.0	-0.003	2.3
Elmira, NY	0.7	0.2	0.2	0.2	-0.0	-0.006	1.6
Fort Walton Beach-Crestview-Destin, FL	1.4	0.4	0.5	0.5	-0.0	-0.002	3.8
Dubuque, IA	0.6	0.1	0.2	0.2	-0.0	-0.007	1.3
Hinesville-Fort Stewart, GA	1.5	0.4	0.5	0.5	-0.0	-0.003	3.9
Albany, GA	2.6	0.7	0.8	0.8	-0.0	-0.002	6.6
Springfield, MO	7.9	2.0	2.2	2.2	-0.0	-0.001	18.0
Ithaca, NY	0.8	0.2	0.2	0.2	-0.0	-0.007	1.8
Sheboygan, WI	0.9	0.2	0.2	0.2	-0.0	-0.007	1.8
Iowa City, IA	1.1	0.3	0.3	0.3	-0.0	-0.005	2.5
Ames, IA	0.5	0.1	0.2	0.2	-0.0	-0.010	1.3
Erie, PA	2.8	0.6	0.7	0.7	-0.0	-0.002	5.4
Panama City-Lynn Haven, FL	1.3	0.4	0.4	0.4	-0.0	-0.004	3.6
Hattiesburg, MS	1.5	0.5	0.5	0.5	-0.0	-0.004	4.2
Lawton, OK	1.0	0.3	0.3	0.3	-0.0	-0.006	2.7
Dothan, AL	1.6	0.5	0.5	0.5	-0.0	-0.004	4.4
Bay City, MI	1.7	0.4	0.4	0.5	-0.0	-0.005	3.5
Joplin, MO	3.0	0.8	0.9	0.9	-0.0	-0.002	7.5
Lubbock, TX	1.3	0.4	0.4	0.4	-0.0	-0.005	3.6
Fort Smith, AR-OK	3.1	0.9	0.9	1.0	-0.0	-0.002	7.8
Amarillo, TX	1.7	0.5	0.6	0.6	-0.0	-0.004	4.9
Cedar Rapids, IA	1.6	0.4	0.4	0.4	-0.0	-0.006	3.5
Appleton, WI	1.7	0.4	0.4	0.4	-0.0	-0.006	3.3
Oshkosh-Neenah, WI	1.6	0.4	0.4	0.4	-0.0	-0.006	3.2
Gulfport-Biloxi, MS	2.9	0.9	0.9	0.9	-0.0	-0.003	7.9
Barnstable Town, MA	0.9	0.3	0.3	0.3	-0.0	-0.009	2.4
Monroe, LA	2.4	0.7	0.7	0.8	-0.0	-0.003	6.3
Topeka, KS	1.8	0.5	0.5	0.5	-0.0	-0.005	4.4

Valdosta, GA	2.6	0.8	0.8	0.9	-0.0	-0.003	7.2
Waterloo-Cedar Falls, IA	1.1	0.3	0.3	0.3	-0.0	-0.009	2.6
Rochester, MN	2.6	0.5	0.6	0.6	-0.0	-0.005	4.8
Lake Charles, LA	2.7	0.8	0.9	0.9	-0.0	-0.003	7.3
Jefferson City, MO	3.2	0.9	0.9	0.9	-0.0	-0.003	7.7
Eau Claire, WI	2.3	0.5	0.5	0.6	-0.0	-0.006	4.3
La Crosse, WI-MN	1.0	0.3	0.3	0.3	-0.0	-0.011	2.4
Binghamton, NY	2.9	0.7	0.8	0.8	-0.0	-0.004	6.1
Columbia, MO	2.7	0.7	0.8	0.8	-0.0	-0.004	6.6
Alexandria, LA	1.8	0.6	0.6	0.7	-0.0	-0.005	5.4
Brunswick, GA	2.8	0.9	0.9	1.0	-0.0	-0.003	8.1
Tallahassee, FL	3.4	1.0	1.1	1.1	-0.0	-0.003	9.3
Sioux City, IA-NE-SD	0.9	0.3	0.3	0.3	-0.0	-0.013	2.6
St. Joseph, MO-KS	2.2	0.6	0.6	0.7	-0.0	-0.006	5.4
Wichita, KS	3.5	1.0	1.0	1.1	-0.0	-0.004	8.7
Omaha-Council Bluffs, NE-IA	7.0	1.5	1.7	1.7	-0.0	-0.003	13.5
Glens Falls, NY	1.0	0.3	0.3	0.4	-0.0	-0.013	3.0
Bismarck, ND	0.8	0.3	0.3	0.3	-0.0	-0.017	2.3
Syracuse, NY	5.3	1.2	1.3	1.3	-0.0	-0.004	10.4
Lincoln, NE	1.9	0.5	0.6	0.6	-0.0	-0.008	4.8
Des Moines, IA	3.1	0.8	0.8	0.9	-0.0	-0.006	6.8
Jacksonville, NC	4.4	1.4	1.5	1.5	-0.0	-0.003	12.7
Wausau, WI	1.5	0.4	0.4	0.5	-0.0	-0.012	3.6
Green Bay, WI	2.9	0.7	0.7	0.8	-0.0	-0.007	6.0
Grand Forks, ND-MN	0.8	0.2	0.3	0.3	-0.0	-0.021	2.2
St. Cloud, MN	3.3	0.7	0.8	0.8	-0.0	-0.008	6.3
Sioux Falls, SD	1.5	0.4	0.5	0.5	-0.1	-0.013	3.9
U a-Rome, NY	2.7	0.7	0.8	0.8	-0.1	-0.009	6.3
Rochester, NY	6.9	1.6	1.7	1.8	-0.1	-0.004	14.1
Albany-Schenectady-Troy, NY	6.9	1.6	1.7	1.8	-0.1	-0.005	14.2
Fargo, ND-MN	1.8	0.5	0.6	0.6	-0.1	-0.019	4.7
Lewiston-Auburn, ME	2.0	0.7	0.8	0.9	-0.1	-0.016	6.8
Duluth, MN-WI	3.0	0.9	1.0	1.1	-0.1	-0.018	8.1
Bangor, ME	2.0	1.2	1.2	1.5	-0.3	-0.024	11.2
Burlington-South Burlington, VT	4.3	1.7	1.8	2.1	-0.3	-0.019	15.7
Portland-South Portland-Biddeford, ME	13.2	4.0	4.3	4.7	-0.4	-0.011	36.9

Table A: Damages and benefits (in millions) by MSA