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AN ECONOMIC ANALYSIS OF U.S PUBLIC TRANSIT CARBON EMISSIONS DYNAMICS

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ABSTRACT

Urban public transit agencies spend billions of dollars each year on workers, durable capital and energy to supply transportation services. During a time of rising concern about climate change, the urban public transit sector has not significantly reduced its carbon footprint. Using data for the nation's transit agencies over the years 2002 to 2019, we benchmark U.S transit agencies with transit agencies in Germany and the United Kingdom. We study U.S urban public sector energy efficiency trends and explain the cross-sectional variation. We present a new operating profits metric that incorporates each transit agency's annual total carbon emissions.

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Introduction

In 2002, the U.S within-city public transit sector created 10.2 million tons of carbon dioxide, and this grew to 11.45 million tons in the year 2019.[1] Over these years, total passenger miles increased by 17.35% from 46.1 billion miles in 2002 to 54.1 billion miles in 2019.[2] Public transit vehicle miles increased by 20% from 3.855 billion to 4.629 billion.[3] Given that carbon dioxide emissions only grew by 12.25% while miles travelled increased by roughly 18%, this indicates that the emissions intensity of public transit has declined over time. If we value a ton of carbon dioxide at $35, then the current climate change externality associated with this sector is roughly $350 million per year.

In this paper, we study the determinants of local public transit's contribution to the global externality of climate change. Consider the Los Angeles Metropolitan Transit Agency. In 2002, this agency created 0.422 million tons of carbon dioxide and in 2019, it created 0.495 million tons. What factors determine a transit agency's total carbon emissions? Major cities have committed themselves to shrinking their carbon footprint, but we document that cities have made relatively slow progress.[4] The Federal Government's officials are aware of this fact. In November 2021, Congress passed a major infrastructure bill that includes $89.9 billion for spending to allow urban public transit agencies to purchase new vehicles including electric buses and to phase out inefficient gas-powered vehicles.[5]

We start by comparing the efficiency dynamics of the United States public transit sector with that in the United Kingdom and Germany. We find that the United States vehicles have the highest carbon emissions per mile and the smallest efficiency gains. Whereas the use of public transit has declined in the United States, the ridership in the UK and Germany is higher and has increased from 2002 to 2019. Our findings build on past work benchmarking national transport energy efficiency (Ziolkowska and Ziolkowski 2015). Past work has also studied the

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[1] This is calculated using the public transit dataset we compile (see the data section). The total emissions include both directly operated and purchased transportation vehicles from all public transit agencies. For the largest 270 agencies, total emissions grew from 9.79 to 9.91 million tons over the same time.
[2] https://www.bts.gov/content/us-passenger-miles
[3] https://www.bts.gov/content/us-vehicle-miles
[4] Los Angeles launched its Green New Deal in 2019, targeting 100% renewable energy use by 2045 and net zero emissions by 2050. New York City's OneNYC 2050 Project aims for the city to achieve carbon neutrality by 2050. Chicago's Climate Action Plan sets the goal to reduce the city's emissions by 80% from 1990 levels by 2050.
LA Green New Deal: https://plan.lamayor.org/
OneNYC 2050: https://onenyc.cityofnewyork.us/
Chicago Climate Action Plan: https://www.chicago.gov/city/en/sites/climate-action-plan/home/2022-planning.html
[5] https://www.whitehouse.gov/briefing-room/statements-releases/2021/11/06/fact-sheet-the-bipartisan-infrastructure-deal/

determinants of the U.S private fleet's efficiency dynamics (Knittel 2011). By comparing the energy efficiency of the US public transit sector to that of private cars and aviation, we document greater progress in efficiency improvements for the private transit sector.

In the next section of the paper, we use panel data at the transit agency level from the U.S. National Transit Database over the years 2002 to 2019. We test several hypotheses related to the environmental performance of different transit agencies over time and at a point in time. Our measure of environmental performance for a transit agency is its carbon dioxide emissions per mile of travel where travel can be at the passenger-mile level or vehicle-mile level. We document a steady decrease in emissions per mile from 2002 to 2019, but reductions in emissions per passenger mile slow down after 2010 because of the decreasing ridership. In the U.S, the ten largest transit agencies supplied 70.3% of the total public transit passenger miles in 2019. When we focus on these agencies, we find that most of them have decreasing emissions per vehicle and passenger mile over time.

Transit agencies features soft budget constraints as cities receive state and federal transfers. Such transfers mean that a transit agency that directly supply services may face less competitive pressure to engage in cost minimization than private transit suppliers. In this case, increases in gas prices may have smaller effects on increasing the public sector fleet's energy efficiency (Kahn, Nickelsburg and Li 2015). Conversely, access to clean capital subsidies may accelerate the public sector's capital replacement rate. In January 2022, the US Post Office ordered 165,000 gas-powered trucks, its largest-scale vehicle purchase in three decades.[6] The Post Office claimed that access to finance has been the main obstacle slowing down electrification, although it receives $25 billion from the Post Office Fund every year. We compare the carbon emissions of transit bus service providers in the same city and year when the miles are supplied by the transit agency versus by a privatized provider. We find that buses operated by privatized providers are more efficient than those directly operated by the public transit agencies, but the public fleet has higher turnover rates and larger efficiency improvements over time.

We decompose how much of these energy efficiency gains is due to scale, composition, and technique effects respectively (Copeland and Taylor 2004). At any point in time, a transit agency's emissions depend on the scale of services supplied (i.e. ridership), transit fleet composition (i.e. buses, light rail, heavy rail), and technique factors (i.e. age of the bus fleet,

[6] https://www.nytimes.com/2022/02/02/climate/postal-service-trucks-electric-climate.html

the types of buses such as natural gas versus diesel fuel, and the emissions intensity of the electricity grid where the transit agency is located). We study the emissions reductions brought by shifts between transit modes, transitions to cleaner energy and more efficient electric grids, and the use of newer and cleaner durables (Li, Kahn, and Nickelsburg 2015). We document that the efficiency improvements vary across transit modes. Emissions per mile decrease when riders switch from inefficient modes such as buses to efficient ones such as subways. On the supply side, emissions decrease when transit agencies substitute older and dirtier capitals with newer and more efficient ones like electric buses.

After studying the national trends in the public transit sector's efficiency gains, we use cross-sectional variations to explore the role of city specific attributes in determining a transit agency's carbon emissions rate. We document that richer, more progressive, and larger cities feature lower carbon emissions per mile. These cities are also more likely to adopt both electric public transit buses and electric school buses.

In the final section of the paper, we present a green accounting approach to incorporate the social costs of the greenhouse gas emissions created by each transit agency. Most U.S transit agencies lose money each year as their operating revenue is less than their operating costs. Labor is the major cost of any transit agency. Jerch, Kahn, and Li (2017) document the role that public sector union power plays in inflating these costs. Meyer, Kain, and Wohl (2013) argue that direct transit subsidies also lead to operating cost escalation. For major transit agencies, we report their operating profits while netting out their carbon emissions externality. By ranking the agencies according to cost efficiency and pollution externality respectively, we find that agencies with larger operating loss tend to have smaller or even negative gains in energy efficiency.

A Carbon Emissions Accounting Framework for Evaluating Transit Agency Performance

Consider transit agency j in NERC power grid region r at year t. This agency's total carbon emissions depend on the total electricity it consumes, the emissions factor for power grid in the agency's region, and the total gallons of fossil fuels consumed.

$$Emissions_{jrt} = KWH_{jrt} * f_{rt} + \sum_{l=1}^{n} fossil\,fuel_{jlt} * E_l \quad (1)$$

In this equation, KWH_{jrt} represents the total electricity consumed by the transit agency and this is multiplied by the regional carbon dioxide emissions factor, f_{rt}. Over time as the grid becomes "greener", this f (pounds of carbon dioxide per KWH of electricity generated) shrinks. Public transit vehicles run on several different (n) types of fossil fuels, each of which has its own emissions factor E_l (pounds of carbon dioxide per gallon of fuel *l*).

This equation embodies scale, composition, and technique effects (Copeland and Taylor 2004). If the total public transit ridership increases, electricity consumption and fossil fuel consumption increase. A composition effect could occur if a transit agency such as the Los Angeles Metropolitan Transit Agency builds a new rail system such as the light rail Exposition Line (Baum-Snow and Kahn 2005). This line has enjoyed increased ridership as it has cannibalized bus rides. In this case, this investment in infrastructure leads to increased electricity consumption and reduced fossil fuel consumption relative to what the agency would have consumed had it not built this new infrastructure. Over time, as transit agencies substitute to cleaner fuels for buses, this introduces another composition shift. As transit agencies increasingly rely on electric buses, this increases electricity consumption and reduces fossil fuel consumption.

Technique effects are likely to vary with respect to the vintages of capital. Equation (1) can be rewritten so that "n" represents the set of fuel types and capital vintages. This allows emissions factor to vary along both dimensions. Newer buses have lower particulate matter emissions than older buses, yet could be more energy intensive than older buses if they feature air conditioning and other quality features. If newer buses are more energy efficient than older buses, this could induce a rebound effect such that mileage increases (Gillingham, Rapson, and Wagner 2020). Such a rebound effect is more likely to be important for private transportation than for public transportation.

Data

The National Transit Database (NTD) provides information on the annual use of different types of fuels and electricity for each transit agency in the United States. [7] The data are reported by transportation mode and service type on the agency level. There are two main service types in our data: direct operation and purchased transportation. The former includes vehicle directly managed by public transit agencies, and the latter is purchased by public agencies but run and maintained by private operators.

The total vehicle miles and passenger miles data are extracted from the Urban Integrated National Transit Database.[8] We merge the vehicle and passenger miles data into the NTD energy dataset by year, agency, mode, and service type. [9] In the regressions we report below, we focus on the largest 270 transit agencies (ranked based on total vehicle miles) from 2002 to 2019 and create a balanced panel.[10]

The fuel emission factors are from Environmental Protection Agency's (EPA) April 2021 data.[11] To calculate the total CO_2 emissions from fuel combustion, we multiply fuel consumption by its emission factor and sum them up (see equation (1) above). The electricity emission factors are compiled from the summary reports of the Emissions & Generation Resource Integrated Database (eGRID).[12] The reports provide the electricity emission factor for each North American Electric Reliability Corporation (NERC) region.[13] To calculate the total CO_2 emissions from electricity generation, we multiply the total electricity use of every unit of observation (year, agency, mode, and service type) by the corresponding regional NERC emission factor (see equation (1) above). We measure energy efficiency by dividing total emissions by vehicle and passenger miles. A vehicle can have low emissions per vehicle mile but high emissions per passenger mile when the ridership is low.

The revenue and cost data of each agency are also extracted from the NTD.[14] We obtain the annual operating expenses and revenues for each agency/mode/service type. The pollution

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[7] https://www.transit.dot.gov/ntd/ntd-data
[8] https://ftis.org/urban_iNTD.aspx
[9] Fare evasion is a problem commonly faced by public transit agencies. Because ridership is calculated based on fares paid, fare evasion leads to an underestimation of passenger miles. In our analysis, emissions per passenger mile would thus be overestimated. Fare evasion won't affect the estimation of vehicle miles, so emissions per vehicle mile remain accurate.
https://mtaig.state.ny.us/assets/pdf/20-17.pdf
[10] In 2019, our 270 agency sample includes 83.3% of the nation's public transit total vehicle miles and 89.7% of the nation's total passenger miles. When only directly operated vehicles are accounted for, our sample covers 94.8% of the nation's total vehicle miles and 97.2% of total passenger miles.
[11] https://www.epa.gov/climateleadership/ghg-emission-factors-hub
[12] https://www.epa.gov/egrid
[13] Data on emissions factors are only available in 2004, 2005, 2007, 2009, 2010, 2012, 2014, 2016, and 2018. For the missing years, we interpolate the value for each NERC region using linear time trend. We categorize each agency into a NERC region based on the reported zip code for its address.
[14] https://www.transit.dot.gov/ntd/data-product/ts21-service-data-and-operating-expenses-time-series-mode-2

externality equals the amount of CO_2 emissions times social cost of carbon. The green operating profit is total revenues minus the sum of operating costs and the pollution externality. For our analysis, we convert nominal costs, revenues, externalities, and profits into real dollars.[15]

Outliers occur in our dataset mainly because of the missing or wrong data on energy consumption. When total emissions are calculated, these data cause the emissions to be extremely high or low. We identify these outliers and replace them with interpolated values based on emissions from the same agency/mode/service unit in other years.[16]

International Public Transit Comparisons

We compare emissions per vehicle and passenger mile of buses in the United States, the United Kingdom, and Germany. The UK bus emissions and mileage data are provided by the UK government.[17] The German bus mileage data is from the website of the Federal Statistical Office of Germany.[18] The bus emissions are calculated using data from the Federal Ministry of Transport and Digital Infrastructure of Germany.[19] We focus on buses because bus miles account for a large proportion of total public transit miles in all of these countries.[20]

From Figure 1A, we see that German buses have the lowest emissions per vehicle mile, whereas the US buses have the highest emission rates. Although UK buses are less efficient

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[15] The real costs and revenues are calculated using the CPI data, with 1983 as the base year. The social cost of carbon is $35/ton in 2021 dollars, approximately $13.11/ton in 1983 dollars.

[16] We identify the outliers of the dataset using emissions per vehicle mile. We use emissions per vehicle mile as the metric because their trends are relatively stable over years (i.e. depend only on vehicle fuel efficiency and not fluctuate a lot as ridership changes from year to year). For each mode and service combination, we replace the top 1% and the lowest 1% of emissions per vehicle mile with their interpolated values. Then, for the outlier observations, we multiply emissions per vehicle mile by total vehicle mile to get the corrected carbon emissions. We use the corrected emissions data to calculate emissions per passenger mile. Data for 199 observations are replaced with interpolated values.

[17] Carbon emissions data: https://www.isccgov.uk/government/statistical-data-sets/energy-and-environment-data-tables-env

Bus mileage data: https://www.gov.uk/government/collections/bus-statistics

[18] https://www-genesis.destatis.de/genesis/online?language=en&sequenz=statistikTabellen&selectionname=46181#abreadcrumb

[19] https://www.bmvi.de/SharedDocs/DE/Artikel/G/verkehr-in-zahlen.html

[20] In 2019, in the US, buses directly operated by public transit agencies travelled 1.59 billion miles, approximately 52.8% of the total vehicle miles by directly operated vehicles. The total passenger mileage of public buses is 12.88 billion miles, accounting for about 34.7% of the total passenger miles of public transit. In the same year, UK buses travelled 1.41 billion miles and German buses 2.01 billion miles. The passenger miles were 16.4 billion and 29.2 billion miles respectively in the UK and Germany.

than German buses, they have achieved larger efficiency gains over time. Their average emissions per vehicle mile decreased by 26.3% from 5.77 pounds/mile in 2002 to 4.25 pounds/mile in 2019. US buses have achieved the lowest gains in efficiency. Their emissions per vehicle mile decrease by 10.5% from 6.29 pounds/mile to 5.63 pounds/mile in the same period of time. German buses achieved a 15.3% efficiency improvement from 4.32 pounds/mile to 3.66 pounds/mile.

The second figure on emissions per passenger mile shows a similar pattern. German buses are the most efficient, with an average of 0.25 pounds per mile in 2019. UK buses show the largest improvements in energy efficiency over time, with a 44% reduction of emissions per passenger mile from 0.66 pounds in 2002 to 0.37 pounds in 2019. The US buses are the most polluting, and their emissions per passenger mile increases slightly from 0.67 pounds per mile in 2002 to 0.7 pounds per mile in 2019. This is mainly due to decreasing bus ridership in recent years.

Figure 2 shows that in Germany and the UK, bus occupancy increased while it decreased in the United States. As of 2019, the ridership is 8.09 people/vehicle mile in the US, 11.61 in the UK, and 14.53 in Germany. In the UK, bus ridership increased by 32.7% from 2002 to 2019. This is potentially because of the road pricing policy in London which started in 2003 (Small 2005). Over the same time, the ridership increased by 8.5% in Germany and decreased by 14.1% in the US. Gas prices are more expensive outside of the United States and Europe's cities are more compact (Glaeser and Kahn 2004). Higher gas prices raise the marginal cost of driving and thus incentivize people to use public transit. When cities are compact, the public transit system is more likely to cover most areas of the cities, so people find it convenient to take public transit.

U.S Energy Efficiency Trends for Public versus Private Transportation

Within the US, we document less progress in energy efficiency gains for public transit than for other transit sectors. In Figure 3A and 3B, we compare the efficiency gains of public transit with that of private cars and aviation from 2002 to 2019. Public transit's energy efficiency is calculated using our NTD dataset. Energy efficiency data for private cars and airplanes are directly obtained or calculated from data provided by the Bureau of Transportation Statistics.[21]

Figure 3A shows the normalized emissions per vehicle mile for these three sectors. We can observe that public transit and airplanes have similar efficiency gains from 2002 to 2019. Emissions per vehicle mile dropped by 18.3% for airplanes and 18.5% for public transit. Although short-distance electric commuter airplanes have been in use, most airplanes travel for longer distance at higher altitude, which requires batteries with much higher energy density. For public transit, despite the rapid innovations of road vehicles in the past two decades, transit agencies are slow in replacing deficient vehicles with cleaner ones. In contrast, private cars' efficiency increased by 32.3% over the same time, nearly twice as large as that of public transit vehicles. Private car owners face a tradeoff with respect to vehicle power, vehicle safety, and pursuing fuel energy efficiency (Anderson and Auffhammer 2014, Knittel 2011).

Figure 3B shows emissions per passenger mile for these three sectors. Despite the significant decrease in emissions per vehicle mile, private cars have the lowest efficiency gains regarding emissions per passenger mile, with only a 13.9% reduction from 2002 to 2019. It is much lower than 21.3% by public transit and 37.9% by airplanes. This is because U.S vehicle drivers often drive alone. In contrast, although emissions per vehicle mile for airplanes have not sharply declined, their ridership increased by 31.7% in the past two decades. This caused a sharp reduction in emissions per passenger mile. Airplanes are more fully occupied than public transit vehicles because private airline companies seek to maximize profits and respond to demand changes. They shut down or use smaller planes to run the routes with low demand. Therefore, despite the similar gains in efficiency per vehicle mile, the aviation sector experiences a larger improvement in efficiency per passenger mile than public transit does (Kahn and Nickelsburg 2016).

Despite the greater efficiency gains by foreign public transit and domestic private transit, we should recognize the downward emissions trend from the US public transit over time. Figure 4A graphs the weighted average of carbon emissions per vehicle mile of all directly operated public transit services from 2002 to 2019. Emissions per vehicle mile steadily

[21] Below are the data sources:
Private cars miles per gallon data: https://www.bts.gov/content/average-fuel-efficiency-us-light-duty-vehicles
Private cars fuel consumption data: https://www.bts.gov/content/light-duty-vehicle-short-wheel-base-and-motorcycle-fuel-consumption-and-travel
Airplanes fuel consumption data: https://www.transtats.bts.gov/fuel.asp
Vehicle miles data for both sectors: https://www.bts.gov/content/us-vehicle-miles
Passenger miles data for both sectors: https://www.bts.gov/content/us-passenger-miles

trend down, dropping by 18.6% from 6.95 pounds in 2002 to 5.66 pounds in 2019. Multiple factors contribute to the improvements in energy efficiency, including the transition to cleaner fuels and the investments in newer vehicles. Baum-Snow and Kahn (2005) investigate how the opening of new transit heavy rail and light rail trains affects urban ridership. They find that very few car drivers substitute to using these new transit modes. Most of the new rail riders are past bus riders who substitute, which we will discuss in the mode composition section. The impact of such substitution on a transit agency's carbon emissions depends on the carbon intensity of the buses and the emissions factor for the electric utilities in the transit agency's NERC region (see the "f" variable in equation (1)).

Figure 4B shows the weighted average of carbon emissions per passenger mile, which fell by 22.3% from 0.484 pound in 2002 to 0.376 pound in 2014. After 2014, emissions levelled off. In 2019, each passenger mile generated 0.382 pound of emissions. As with emissions per vehicle mile, emissions per passenger mile decreased due to technological progress. Efficiency did not increase after 2014 as the ridership of public transit vehicles has dropped by over 11% since then.

In Figure 5A and 5B, we plot the emissions per vehicle mile and per passenger mile respetively for four of the largest urban transit agencies in the US, including Los Angeles County Metropolitan Transportation Authority, Chicago Transit Authority, MTA New York City Transit, and Massachusetts Bay Transportation Authority in Boston.[22] To obtain an apple-to-apple comparison across cities, we only include buses and subways in our analysis. These two figures demonstrate that the efficiency improvement trands within cities are generally consistent with the national trends. Emissions per mile decreases steadily in Chicago, New York City, and Boston. Los Angeles is the only anomaly. MTA New York City Transit has the lowest emissions per mile and the largest efficiency improvement among these four agencies.[23]

[22] In 2019, these four agencies supplied 17.8 billion passenger miles, roughly 37% of the national total. MTA New York City Transit has a total of 12.15 billion passenger miles, the highest among all public transit agencies. The passenger miles are 1.96 billion, 1.76 billion, and 0.96 billion in Chicago, Los Angeles, and Boston respectively.

[23] In 2019, MTA New York City Transit has the lowest emissions per vehicle mile, about 3.94 pounds, much lower than the national average. Chicago's emissions level is slightly higher than the national average, and Boston's approximately equals the national level. Their emissions per vehicle mile are 6.1 and 5.61 pounds respectively. For Los Angeles County Metropolitan Transportation Authority, each additional vehicle mile produces 8.92 pounds of emissions in 2019. MTA NYC Transit has the largest emissions reduction among these four agencies, by 34.5% from 2002 to 2019. Over the same time, Chicago Transit Authority's emissions per vehicle mile decreased by 24.5% and Massachusetts Bay Transportation Authority's by 23.3%, both larger than the national average reduction. Energy efficiency decreases by 12.8% for the Los Angeles County Metropolitan Transportation Authority. MTA NYC Transit currently has one of the cleanest fleets in the US, with more than 2000 all-electric or hybrid electric buses, and it has also retrofitted most of its diesel buses with diesel particulate filters.

U.S Public Transit Regression Results

To study the national time trends in public transit agency energy efficiency, we estimate the following regression specifications for transit agency j in year t:

$$log(\,emissions\ per\ mile_{jt}) = \beta_0 + \beta_1 trend\ before\ 2010_{jt} + \beta_2 trend\ since\ 2010_{jt} + \beta_3\, log(\,ridership_{jt}) + \alpha_j + \varepsilon_{jt} \qquad (2)$$

In equation (2), we fit emissions per mile and spline the time trend to allow for a different slope before and after 2010. All regressions are weighted by miles, which can refer to total vehicle or passenger miles. Ridership is the passenger miles per vehicle miles, a measure of the efficiency of the system. An inefficient system features low occupancy vehicles travelling around the city. We control for agency-fixed effects (α_j). The standard errors are clustered at the agency level.

In Table 1, columns (1) and (2) show the time trends for all transit agency activity directly operated by the transit agency (i.e. no privatized trips). The time trends are both negative, and the coefficients are statistically significant. Emissions per vehicle mile on average declined by 1.18% per year before 2010 and by 1.45% annually after 2010. Emissions per passenger mile decreased annually by 1.76% before 2010 and 1.68% since 2010.[24] From 2002 to 2019, vehicle miles increased by 20%, and passenger miles increased by 17.3%. Yet, emissions per passenger mile decreased faster than emissions per vehicle mile because of the

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Trends in emissions per passenger mile exhibit similar patterns as emissions per vehicle mile. MTA NYC Transit has the largest decrease in emissions per passenger mile, by 46.3% from 0.285 pound in 2002 to 0.153 pound in 2019. A significant portion of the improvements comes from the increasing ridership, which grew by 22.4% over the same time. Chicago Transit Authority's emissions per passenger mile dropped by 28.1% from 0.577 to 0.415 pounds and Massachusetts Bay Transportation Authority's by 23.9% from 0.427 to 0.324 pounds. Chicago's current emissions level is similar to the national level, and Boston's is 21% lower. The Los Angeles County Metropolitan Transportation Authority's emissions per passenger mile increased by 23.6% from 0.492 to 0.608 pounds.

[24] The NTD dataset includes information on 896 public transit agencies, 835 of which own directly operated vehicles. Among these 835 agencies, we have non-zero fuel consumption data for 705 of them. Results are similar when we run the same regressions on these 705 agencies. Trends are significantly negative at the 1% level both before and since 2010. Trends are more negative before 2010 both for emissions per vehicle and per passenger mile. Emissions per vehicle mile decreased by 1.54% annually before 2010 and 1.42% onward. Emissions per passenger mile decreased by 2.3% and 1.67% per year respectively.
We also drop the ridership variable from equation (2) and estimate it on the largest 270 agencies without weighting by miles. Under this alternative specification, all trend variables are significantly negative at the 1% level. Emissions per vehicle mile declined by 0.3% annually before 2010 and 0.8% onward. Emissions per passenger mile decreased by 2.36% per year before 2010 and 0.75% onward.

shifts in transit mode composition. More passenger miles are travelled on cleaner modes. Nevertheless, reductions in emissions per passenger mile slow down slightly after 2010. In column (2), ridership is significantly negative as expected. Emissions per mile are lower when vehicles are more fully occupied.

Does Transit Privatization Increase Energy Efficiency?

Public transit can be operated by public transit agencies or private transit providers. In recent decades, some transit agencies have chosen to privatize some of their bus service. For example, consider Orange County Transportation Authority in Southern California. In the year 2010, 9.7% of its total bus miles were travelled on purchased buses operated by private transit providers while in 2019, 41.5% were. Its passenger miles share on purchased transportation jumped from 2.75% to 32.1% over the same time. Most other agencies show a smaller yet positive change in privatized mileage share. The national vehicle mile share of private buses increased from 5.77% in 2010 to 9.24% in 2019 and passenger mile share from 4.17% to 6.18%. As shown by Jerch, Kahn, and Li (2017), agencies can reduce their average costs by privatizing bus services. Private providers of transit service have a greater incentive to engage in cost minimization and to more efficiently utilize buses and energy. We test this claim below.

In Table 1, columns (3) and (4) provide a direct comparison of directly operated bus miles and purchased transportation bus miles energy efficiency. Both service types are owned by public transit agencies, but the latter is operated by private transit providers. We study whether public transit agencies or private transit providers are more likely to use efficient vehicles and upgrade dirty capitals. We estimate the following regression specifications for buses of service type i from transit agency j in year t, where the year is 2008 onward:

$$log(emissions\ per\ mile_{jit}) = \beta_0 + \beta_1 trend_{jit} + \beta_2\, log(ridership_{jit}) + \beta_3 public_{jit} + \beta_4 trend \times public_{jit} + \alpha_j + \varepsilon_{jit} \qquad (3)$$

In equation (3), mile is either vehicle or passenger mile, and ridership is passenger miles per vehicle mile. We weight regressions by miles. Public is a dummy variable that equals 1 when the bus is directly operated. We control for agency-fixed effects (α_j). The standard errors are calculated clustering at the agency level.

In both columns, the public dummy variable has significantly positive coefficients. Directly operated buses have much higher emissions per mile than vehicles operated by private providers. They produce 15.9% more emissions per vehicle mile and 17.9% more per passenger mile on average. Nevertheless, the negative coefficients of the interaction term show that directly operated buses have larger efficiency gains over time. For directly operated buses, the annual decline in emissions per vehicle mile is 1.17% more than their private counterparts, and the decline in emissions per passenger mile is 1.46% more. These estimates are significant at the 5% level. Although the public bus fleet is overall older, the turnover rate of public buses is higher. The unweighted average public bus fleet age is 8.24 years, and that of the private fleet is 7.42 years. However, when weighted by vehicle miles, the average age of the public fleet drops to 7.11 years, while the private fleet age decreases only slightly to 7.26 years.[25]

The trend variable has a positive and statistically insignificant slope. Higher ridership leads to higher emissions per vehicle mile but lower emissions per passenger mile. Buses with high ridership need to stop more often and for longer time at bus stops. Also, public transit ridership is higher in populated cities with more congestion. These factors cause higher emissions per vehicle mile. Emissions per passenger mile decrease when there are more bus riders.

Emission Reductions from Mode Composition Shifts from Bus to Rail

Over the last 40 years, many major cities have expanded their rail transit systems (Baum-Snow and Kahn 2005). Today, Los Angeles is investing billions to extend the Purple Line Subway that will connect downtown Los Angeles to the Santa Monica beach. This investment will be finished sometime in the 2030s. The Biden Administration's infrastructure bill provides enhanced funding for such infrastructure. It is unlikely that cities would build such infrastructure without major federal subsidies. These investments induce ridership shifts. Baum-Snow and Kahn (2005) argue that few private vehicle riders substitute to public transit because of such rail expansions. Instead, past bus riders substitute to rail. We now explore this claim.

Figure 6A shows the percentage of passenger miles on each mode over time. For buses,

[25] These are calculated using the bus inventory data for the largest 270 agencies in 2019.

their share of total passenger miles decreases from 40.1% in 2002 to 28.8% in 2019. Subways and rails both show increasing shares. The subway's share rises from 33.8% to 38.8%, and rail's from 24.2% to 27.3%. Many small cities don't have rails. When we calculate the mileage shares for the 35 largest transit systems, the substitution from buses to rails remains evident. Passenger mile share from buses dropped from 32.2% in 2002 to 22.7% in 2019. Share of subway increased from 39% to 43.6% and other rail from 27.6% to 30.4%.

Figure 6B shows that different transit modes have different rates of efficiency improvements. Compared with subway and rail, the bus mode has the lowest efficiency gains. Its emissions per vehicle mile decreased by 11.1% from 6.28 pounds in 2002 to 5.58 in 2019. The same metric decreased by 37.4% for subway (6.93 pounds to 4.34 pounds) and 24% for rail (11.45 pounds to 8.7 pounds). Average emissions per mile decrease as passengers substitute bus with subway because subway has lower emissions per mile and faster emission reductions. Granted, rails (other than subways) still have higher net emissions per mile than buses, despite their faster improvements in emission reductions. Most services run on rails are intercity, the increasing passenger mile share of rails may be due to the substitution from intercity buses or private cars.

The Rising Demand for Electric Buses

Given that the transportation sector produces a large share of U.S carbon emissions, there is both a private sector and a public sector push to simultaneously electrify the vehicle fleet and to green the grid. President Biden has announced his goal that a growing share of cars be electric vehicles. Electric vehicles contribute to a net emission reduction only when the regional electric grid is clean (Holland et. al. 2016). If the electricity is generated using polluting fuels such as coals, electric vehicles might generate more pollutions than diesel or gas vehicles. From 2002 to 2019, the US electric grids' efficiency improved by 38%. The environmental benefits of electric buses increase as electric grids become greener. Carbon emissions per megawatt decline in all NERC regions, although there are regional heterogeneities in efficiency gains.

Given that big city transit agencies often feature a progressive mayor and that transit agencies rely on Federal subsidies for capital expenditures, we posit that the public transit's share of electric buses would grow faster than the private vehicle electric share. Table 2 shows the percentage of vehicle miles travelled on each of the energy sources in 2012 and 2019 for directly operated and purchased transportation buses respectively. Overall, a larger proportion of bus miles are run on cleaner energy in 2019 than in 2012.[26] The privatized bus fleets are cleaner overall, but the public bus fleets show more rapid transition to cleaner fuels.[27]

Notably, for directly operated buses, the mileage shares of electric buses increase from 0.02% to 0.25%. The twelvefold increase demonstrates the recent growth but the overall share is still tiny. This small share is likely to be due to the durability of public transit buses.[28] It would take at least ten years to electrify the entire on-road bus stock, given 100% annual market share of electric buses among all bus purchases.[29] Among the transit buses manufactured between 2012 and 2019, 1.35% of directly operated ones and 1.71% of purchased transportation ones are electric. Private transit providers purchase slightly more electric buses,

The bus fleet electrification rate in the US is lower than other major economies such as the European Union and China.[30] Some barriers to bus electrification include the lack of charging infrastructure and the high fixed costs of electric buses. Because of the Buy American Act, transit agencies are required to purchase electric buses from domestic manufacturers when receiving federal subsidies. Shielded from competition, these firms manufacture more expensive yet less efficient electric buses than their foreign counterparts such as BYD (Li, Kahn, and Nickelsburg 2015).

When a bus operator substitutes from a fossil fuel bus to an electric bus, this induces two different environmental impacts. First, carbon emissions may decline if the electricity grid is clean. The annual climate change externality reduction is the difference between the social cost of emissions from fuels and from electricity generation. It can be calculated by Miles*Gallons Per Mile*Fuel Emissions Factor*35 - Miles*KWH/mile*Grid Emissions Factor *35. This is shown in the downward trend of emissions per mile of the US buses.

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[26] For directly operated buses, among all energy sources displayed, diesel is the only fuel whose share of vehicle miles drop. Many buses upgrade from using diesel to cleaner fuels. The vehicle mile share by CNG increases most prominently. It rises by 10.07% from 2012 to 2019. The use of hybrid diesels has the second-highest increase. The mileage shares of gasoline and hybrid gasoline vehicles both increase slightly.

[27] For the privatized fleet, a smaller proportion of vehicle miles is run on dirty fuels like diesels. Bus electrification is more rapid in the private sector. The mileage shares of electric buses increase by 0.36% for purchased transportation buses versus 0.23% by directly operated buses from 2012 to 2019. Nevertheless, the substitution from diesel to other cleaner fuels like natural gas is more prominent for the public fleet. Unlike public buses, privatized buses' mileage shares of diesel and gasoline both increase.

[28] In 2019, the average age (weighted on vehicle miles) of all directly operated buses is 7.12 years, and that of purchased transportation buses is 6.79 years. The unweighted average age is 7.81 and 6.84 years respectively.

[29] https://www.rff.org/publications/issue-briefs/an-analysis-of-us-subsidies-for-electric-buses-and-freight-trucks/

[30] IEA, Electric bus registrations by region, 2015-2020, IEA, Paris https://www.iea.org/data-and-statistics/charts/electric-bus-registrations-by-region-2015-2020

The second impact of this bus substitution is to reduce PM2.5 emissions for those on the bus and those who walk in close proximity to the bus. Public health studies have quantified bus riders' and pedestrians' exposure to bus emissions. Sabin et al. (2005) find that the concentration of pollutants such as PM2.5 is several times higher inside diesel buses than CNG buses. Emissions per passenger mile decrease as more people ride public transit. However, without the adoption of cleaner vehicles, an unintended consequence is that more people are exposed to the pollution on the transit network, causing more negative externalities. Transit pollution is especially harmful to children. School bus commutes are estimated to cause one-third of children's daily black carbon exposure if they commute in high-emission school buses (Behrentz et al. 2005). Aside from public transit riders, transit emissions also have disproportionally large negative impacts on the health of pedestrians and near-road residents (Hu et al. 2012).

Bus Vehicle Vintage Cohort Effects and Make Effects

Although the demand for cleaner vehicles like electric buses is rising, the transportation capital stock is highly durable, which means that innovation for recent vintages only slowly affects the average emissions of the fleet at a given point in time. Kahn (1996) documents that California vehicles built in the early 1990s feature much lower air pollution emissions than vehicles built in the early 1970s. Such vintage effect research seeks to disentangle age effects from model effects. The same issues arise in studying bus capital vintage effects.

Table 3 shows how upgrading to cleaner durables affects the total emissions from public transit buses. The data for these regressions come from the 2012 and 2019 inventory data from NTD.[31] We hypothesize that newer vehicles produce fewer emissions. To test these hypotheses, we estimate the following regression specifications for buses from agency j in year t using two cross-sections of data from 2012 and 2019. The unit of analysis is a transit agency/year.

$$log(emissions_{jt}) = \beta_0 + \beta_1 log(mileage_{jt}) + \beta_2 log(mileage_{jt} \times year2019) + \beta_3 year2019 + \beta_4 public + \beta_{vintage} X_{vintage} + \beta_{type} X_{type} + \varepsilon_{jt} \quad (4)$$

[31] https://www.transit.dot.gov/ntd/ntd-data

To estimate equation (4), we divide buses from each agency into seven vintage categories based on each bus's manufacture year. Each five-year interval from 1990 to 2020 is a category, and model year before 1990 is the base category. We also divide buses into three types based on their manufacturer: New Flyer, Gillig Corporation, or other. We choose other as the base type. We include these make fixed effects to test whether individual bus makers differ with respect to the environmental performance of their buses. We study whether the newer fleets are more efficient. This econometric specification enables us to disentangle age effects from make effects.

In equation (4), mileage refers to an agency's total bus miles in 2012 or 2019. Public dummy equals 1 for buses directly operated by the agency. $X_{vintage}$ is a vector of bus mileage share by each of the seven vintage categories (except the base category), and $\beta_{vintage}$ is a vector of coefficients for each vintage group. Similarly, X_{type} is a vector of mileage share by each of the three bus types (except the base type), and β_{type} is a vector of coefficients. The standard errors are clustered at the agency level. Table 3 displays the results from equation (4).

The year 2019 dummy has a positive slope in all columns and significant in columns (1) and (2). This shows that buses generate more emissions in 2019 than in 2012. However, the interaction term between the 2019 dummy and total mileage has negative coefficient in all columns and significant in columns (1) and (2). Each additional mile generates fewer emissions in 2019, consistent with our previous finding that the public transit fleet becomes greener over time.

We calculate the share of mileage by buses manufactured during each 5-year period. The omitted category is years before 1990. The passenger miles share from all periods have negative coefficients. Buses manufactured later than 1990 generate fewer emissions than those before 1990. These coefficients mostly have increasing absolute values. This confirms our expectation that newer capitals are more energy efficient. On average, when buses manufactured after 2015 are used to substitute those before 1990 to run an additional 1% of total mileage, total emissions would decline by slightly over 1.7%.

The public dummy has a significant positive coefficient. For public and privatized bus fleets with the same age and make composition and driven the same distance, directly operated buses produce 18.9% more emissions than purchased transportation buses in column (3) and 14.6% more in column (4). If two fleets have the same age and make composition, they may not have the same energy efficiency because fuel type is another key determinant of bus emissions. Buses bought in the same year from the same manufacturer can vary in energy efficiency if they are powered by different energy sources.[32] Private transit providers are more likely to purchase energy-efficient models, usually more expensive. Therefore, at a given point in time, the private bus fleet generally causes less emission per mile, although we have previously documented that the public fleet features more rapid transition to clean energy over time (i.e. Private fleets are more efficient, but the energy efficiency of the public fleet is catching up).

New Flyer and the Gillig Corporation are the two largest transit vehicle manufacturers in the US. In 2019, 18.6% of bus miles use New Flyer buses and 53.2% use Gillig Corporation buses. The coefficients of mileage shares by New Flyer and Gillig Corporation are both positive and statistically significant. Compared with smaller manufacturers, these two large manufacturers produce less efficient buses. It remains an open question whether these companies will invest more to develop more energy efficient buses as the Federal Government commits itself to reducing national greenhouse gas emissions.

Unlike private transit providers, public transit agencies tend to purchase vehicles from large manufacturers because of the Buy American Act. For directly operated buses, 19.7% of total bus miles are run by vehicles from New Flyer and 58.3% from Gillig Corporation. The same metrics are 12.9% and 29% for purchased transportation buses. Private suppliers of bus miles do not face soft budget constraints and are more likely to engage in cost minimization. When the price of gasoline is higher, such private providers have an incentive to substitute to more energy efficient vehicles. This lowers the carbon footprint as the "rebound effect" associated with public transit is likely to be low.

Cross-Sectional Determinants of Low Carbon Emissions

In previous sections, we have documented the national progress in public transit emissions reductions and examined the sources of these reductions. Nevertheless, public transit's energy efficiency varies across regions. More educated, more progressive places in the United States such as Berkeley, California are home to residents who live a "greener lifestyle" in terms of having a smaller carbon footprint (Kahn 2007). On explanation for this

[32] For example, New Flyer manufactures six different types of buses run on different energy sources, ranging from clean diesel to electricity.
https://www.newflyer.com/new-flyer-buses-meet-the-xcelsior-family/

fact is the voluntary restraint hypothesis that posits that some segments of the population actively do not want to pollute even if they do not face a Pigouvian tax (Costa and Kahn 2013, Kotchen and Moore 2008).

In this section, we include county level correlates to explain cross-sectional variation in the carbon footprint from public transit. We test for the role of education and progressive voting as correlates of low emissions per mile of public transit. We study the effect of these factors on public transit emissions using American Community Survey data.[33] We hypothesize that emissions per mile are lower in regions with more liberal voters, higher level of education, and lower population density. To test these claims, we run the following regressions on all directly operated vehicles for transit agency j (located in county i) at time t:

$$log(\, emissions\ per\ mile_{jt}) = \beta_0 + \beta_1 Republican\ votes_i + \beta_2 college\ graduates_i + \beta_3 \log(Population_i) + \mu_t + \omega_j + \varepsilon_{jt} \qquad (5)$$

In the above equation, republican votes refer to the percentage of votes for the Republican candidate in the 2020 presidential election, and college graduates refer to the percentage of adult population age over 25 that has a bachelor's degree. We control for year fixed effects (μ_t) and region fixed effects (ω_j). Each agency is classified into one of the four regions (Northeast, Midwest, South, and West) based on the county it is located in. The standard errors are clustered at the agency level. In Table 4, columns (1) and (2) display the results of equation (5).

In both columns, Republican votes have a positive coefficient, though it is insignificant when region fixed effects are included. Overall public transit vehicles in liberal regions have lower emissions per passenger mile. When 1% more voters vote for Republican candidates, on average, emissions increase by 1.88% without region fixed effects and by 0.64% with region fixed effects. The college graduate variable's coefficient is negative and statistically significant. All else equal, a ten-percentage point increase in the county's share of adults who are college graduates is associated with a 19% reduction in carbon emissions (see column (1)).

Emissions per mile are lower in cities with a larger population. When population rises

[33] https://www.census.gov/programs-surveys/acs/data.html

by 1%, emissions per passenger mile decline by 0.06% and by 0.13% respectively without and with region fixed effects. The coefficient is statistically significant only in column (2). The public transit ridership is higher in densely populated cities, whereas most people drive in cities with smaller population density. This leads to lower emissions per passenger mile in populated cities.

Electric School Bus Adoption versus Electric Public Transit Bus Adoption

Located in different regions, transit agencies are not equally incentivized to invest in cleaner vehicles. This can explain a large proportion of regional variations in public transit emissions. We explore whether the county level determinants of whether a transit agency introduces electric buses differ from whether local school districts incorporate electric school buses and thus phase out old diesel buses. We view this comparison of different types of public buses as offering additional evidence on the plausibility of our core hypothesis concerning local environmentalism.

School districts around the nation are increasingly considering adopting electric buses to replace diesel buses. Such adoption reduces child exposure to local PM2.5 levels (Behrentz et al. 2005). Our bus inventory data are from the NTD dataset, and our electric school bus data are provided by the World Resources Institute.[34] We estimate the following logistic regression specifications for transit agency/school district i (located in county k) using cross-sectional data in 2019 (for public transit buses) and in 2020 (for school buses). In the equation below, electric bus is a dummy variable equal to 1 if the transit agency has electric buses in 2019 or if the school district has electric school buses in 2020.[35]

$$Electric\ Bus_i = \beta_0 + \beta_1 Republican\ votes_k + \beta_2 college\ graduates_k + \beta_3 \log(Population_k) + \varepsilon_i \tag{6}$$

In Table 4, columns (3) and (4) show the estimation of equation (6). Electric bus

[34] https://datasets.wri.org/dataset/electric_school_bus_adoption

[35] In 2019, 42 of the largest 270 transit agencies owned electric buses. In 2012, only three of the largest 270 agencies had electric buses. Among the 11352 public school districts we have data for, 331 of them had at least one electric school bus in 2020. Despite the efforts to electrify public transit, electric buses make up only a small share of the bus fleet.

adoption is higher in liberal, educated, and more populated regions. This is consistent with our previous finding that vehicles in these regions have lower emissions per mile. When 10% more of the adult population get a bachelor degree, the log odds of electric bus adoption increase by 0.48. The log odds of electric school bus adoption rise by 0.13. Both are significant at the 1% level. Political ideology is more significant to electric school bus adoption than in the electrification of public transit buses. A 10% increase in votes for Republicans is associated with a 0.17 decrease in the log odds of electric school bus. This estimate is statistically significant at the 1% level. The coefficient of Republican votes is negative but statistically insignificant in column (3). The soft budget constraint faced by public transit agencies slows down the electrification of bus fleets. In contrast, approximately 1/3 of the school buses in the US are privatized. The private sector operators more electric school buses in educated and liberal regions because of the higher local demand for electric transit. They also seek to economize on energy expenditure to maximize profits, which simultaneously creates public goods such as better air quality.

Incorporating Green Accounting in Measuring Public Transit Agency Operating Profits

Pigouvian logic argues that the public sector is needed to reduce the social costs created by the private sector. In this section, we measure the social cost of the public sector's transit service production in the absence of a Pigouvian Tax on the public sector.[36]

We use the costs and revenues data for each public transit agency from 2002 to 2019 to calculate its real costs, real revenues, and climate change externality associated with each dollar of revenue.[37] The externality is calculated using equation (1), and we translate this carbon emissions into a dollar value by multiplying by $35. [38]

Unlike private transit providers, public transit agencies cannot choose their profit-maximizing output (i.e. vehicle and passenger miles supplied) and have to supply the regulated level of output (Williams 1979). This causes most US transit agencies' to bear large operating loss and rely heavily on government subsidies. We weight the largest 270 public transit agencies by vehicle miles and calculate the national average of operating costs per dollar of

[36] We recognize that in the absence of public transit, the private sector's negative externality would have been even larger.

[37] https://www.transit.dot.gov/ntd/data-product/ts21-service-data-and-operating-expenses-time-series-mode-2

[38] As with real revenue and real cost, we adjust externality using CPI from 1983. The real social cost of carbon is roughly $13.1 in 1983 dollars.

revenues.[39] In 2002, on average, an agency spent $3.74 for $1 of revenue. For the median agency, the cost-effectiveness was $2.98 of cost per $1 of return. The distribution is right-skewed with a few agencies making much larger losses. In 2019, an average agency spent $4.61 for $1 dollar of return, and the median agency spent $3.49. Compared with in 2002, public transit agencies made more loss in 2019. The loss went up due to the decreasing ridership and the pressure from worker unions that demand higher wages. The overall cost-efficiency would increase if transit agencies can accommodate commuters' demand for new routes and modes (e.g. more subways and fewer buses) and shut down unused capitals.

In 2002, on average, each dollar of revenue was associated with 4.89 cents of climate change externality, and the median externality is 3.96 cents. The distribution of pollution externality is right-skewed. Some agencies are polluting much more than the average agencies. In 2019, the average externality increased slightly to 4.95 cents per dollar of revenue, but the median externality dropped by 12.6% to 3.46 cents.

In Table 5, we list the statistics on mileage, costs, and carbon efficiency of the fifteen largest transit agencies in the US (ranked by total passenger miles) in 2002 and 2019. Among these agencies, twelve show an increase in vehicle miles, but only eight show a corresponding increase in passenger miles. From 2002 to 2019, ten of the fifteen agencies made more loss. Agencies making larger loss tend to be those with significant decrease in ridership. Nevertheless, most of these largest agencies make smaller loss than an average agency. In 2019, for the fifteen largest agencies, each dollar of revenue was associated with $2.86 of spending, 38% lower than the national average. The largest agencies also show more progress in pollution reduction. Eleven of them reduced the negative externality from emissions. In 2019, most of them had smaller negative externality compared to other public transit agencies. On average, the fifteen largest agencies produced 2.2 cents of negative externality for each dollar of revenue in 2019. This is 55% lower than the national average and 44% lower than the median. This implies economies of scale in pollution reduction.

Do Transit Subsidies Improve Energy Efficiency?

Subsidized agencies could use their government subsidies to invest in energy efficiency improvements and swap out dirty vehicles. Federal transfers soften transit agencies' budget

[39] We drop the top and the bottom 1% when calculating the national statistics.

constraints so that they can retire inefficient vehicles earlier than if there wasn't any funding (Li, Kahn, and Nickelsburg 2015). Transit agency expenditure is made up of operating costs and capital costs. While agencies receive greater government transfers, a large proportion of the funding is spent on operating costs such as labor and vehicle maintenance.[40] If an agency has a smaller operating loss, it can allocate more government funding to upgrade its capital stock.

Marginal operating cost declines as the total passenger miles increases (Williams 1979). Agencies with higher ridership can also collect more revenues to cover the operating costs, so they have more leftover funding to purchase cleaner vehicles. When transit agencies use more efficient vehicles, their total operating costs further decrease as the "rebound effect" is likely to be small for the public sector. Through this self re-enforcing process, emission reductions may exhibit increasing returns to scale.

Parry and Small (2009) document that government subsidies are effective in lowering negative externalities (including congestion, pollution, and accident externalities) from urban public transit due to the scale effect. In Figure 7, we explore the role of transit subsidies and the economies of scale in pollution reductions, using data from the 75 largest transit agencies.[41] Figure 7A and 7B show how pollution externality is correlated to an agency's cost-effectiveness (defined as operating cost/revenue) and total passenger miles.

Figure 7A reports a strong positive correlation between the increase in pollution externality and the increase in operating loss (i.e. rising cost per dollar revenue) from 2010 to 2019. Agencies face budget constraints. If they have to use government transfers to compensate for the operating loss, they have less funding to upgrade capital.

Figure 7B plots the change in pollution externality against the increase in total passenger miles. The correlation is negative, though less strong. The emission reductions is greater for agencies with larger increases in passenger miles. As ridership rises, agencies gain more revenues to fund their operating expenditure and can spend more on cleaner capital. These efficient vehicles reduce both the operating and the social costs of transit service provision.

[40] https://crsreports.congress.gov/product/pdf/R/R47002/1
In the past decade, government funding for public transit increased by roughly 30% from $10 billion to $13 billion. Operating costs account for two-thirds of transit agencies' total costs, and capital costs make up the other one-third. Operating revenues cover only one-fourth of the total costs, with the rest subsidized by the government. Federal transfers mainly support capital investments, while state and local government transfers finance operating loss.

[41] We recognize that pollution externality only accounts for a small fraction of total negative externalities from public transit. Congestion makes up a large proportion of the externalities.

The declines in marginal costs lead to increasing returns to scale in pollution reductions. The graph shows that large agencies overall outperform small agencies in reducing the externality from carbon emissions.

Conclusion

We have used a twenty-year panel dataset for U.S transit agencies to explore how the carbon footprint of these agencies has evolved over time. We document significant efficiency improvements in the US public transit sector from 2002 to 2019, but the transit sector in Europe had much larger efficiency gains over the same time. Within the US, privatized road transportation and aviation are more efficient than public transit. Major sources of emissions reductions from public transit include the substitution from bus to rail, transition to cleaner energy, and investments in newer capitals. Agencies in more liberal, educated, and populated regions show larger emissions reductions and are more likely to adopt electric buses. We examine the cost dynamics of transit agencies and find that cost-inefficient agencies also tend to be energy-inefficient. There are economies of scale in pollution reductions in the public transit sector.

Federal subsidies play a key role in financing transit agencies' investments in cleaner capitals. However, in this paper, we have argued that public transit agencies do not face the right incentives to lower the carbon emissions of their current fleet. The role of the Buy America Act in limiting the imports of high efficiency rail and bus capital merits more research. Protected from foreign competitions, the largest bus manufacturers have monopoly power and are disincentivized from producing efficient vehicles at more affordable prices. Future research could study whether American public transit would achieve greater efficiency gains if transit agencies can purchase cheaper yet more efficient vehicles from abroad.

As transit agencies phase out diesel vehicles, this would lower the transit emissions in the US. However, diesel vehicles are long-lived durables. Inefficient vehicles that fail emissions tests in the US would be exported to developing countries, where the demand for lower-quality vehicles is higher. These countries have low vehicle retirement rates, so vehicles' lifetime emissions would rise if they are exported (Davis and Kahn 2010). Future research could study international trade in public transit buses. A new "cash for clunkers" program would reduce the likelihood of leakage as these buses are exported to poorer nations and used for longer periods of time.

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Figure 1A. Bus Emissions Per Vehicle Mile in the US, the UK, and Germany

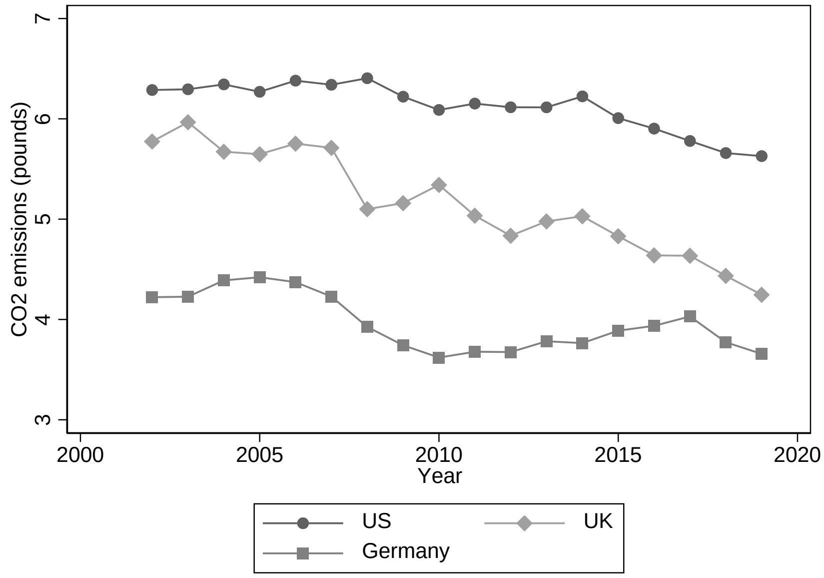
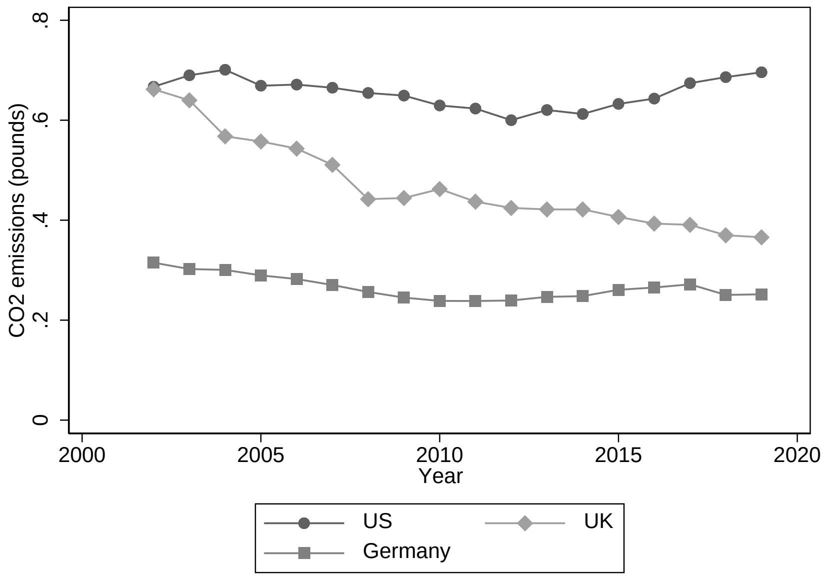
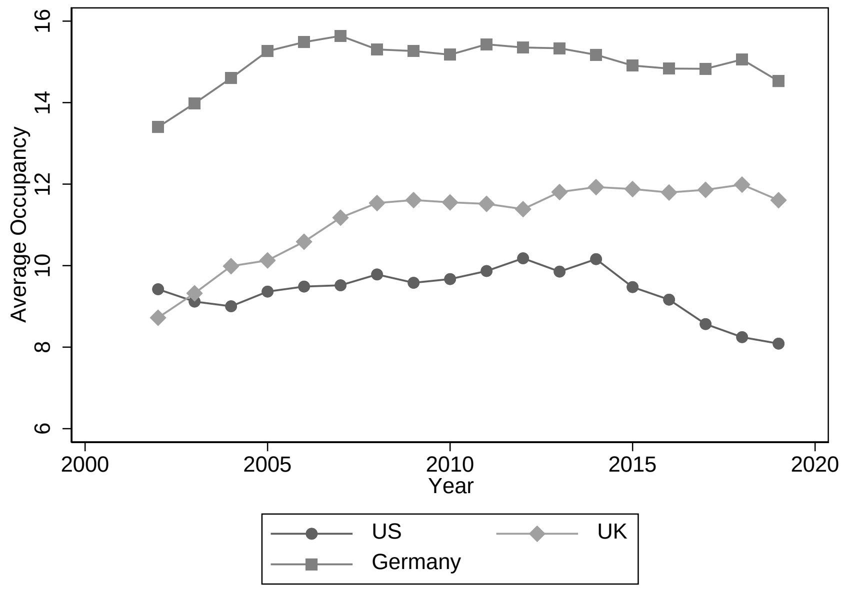


Figure 1B. Bus Emissions Per Passenger Mile in the US, the UK, and Germany



Notes: CO2 emissions are measured in pounds, and bus mileages are measured in miles. We convert the units in the UK and Germany data, which are originally in tons and kilometers. We interpolate the vehicle and passenger miles of German buses in 2002 and 2003 because the data is available from 2004. Emissions data of German buses are not directly available. The Federal Ministry of Transport and Digital Infrastructure provides the total emissions from German public transit and the energy use of each transit mode. We assume all public transit modes have the same energy efficiency in Germany and calculate the emissions from buses based on the proportion of energy use across modes.

Figure 2. Average Bus Ridership in the US, the UK, and Germany



Notes: The average ridership is calculated using total passenger miles divided by total vehicle miles. In the UK and Germany, total mileage data is only available on the national level. For the US, we calculate the ridership of buses from each agency, weight them on vehicle miles, and calculate the weighted average of occupancy rates.

Figure 3A. Emissions Per Vehicle Mile by Sector

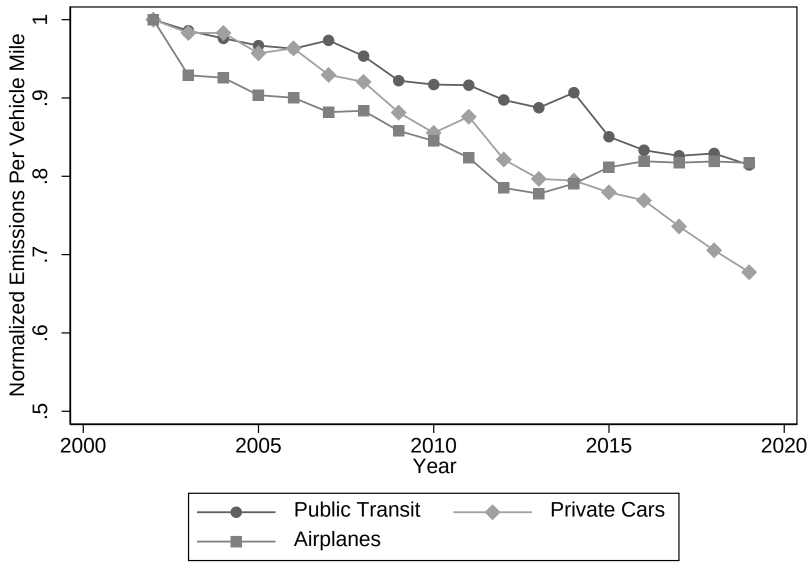
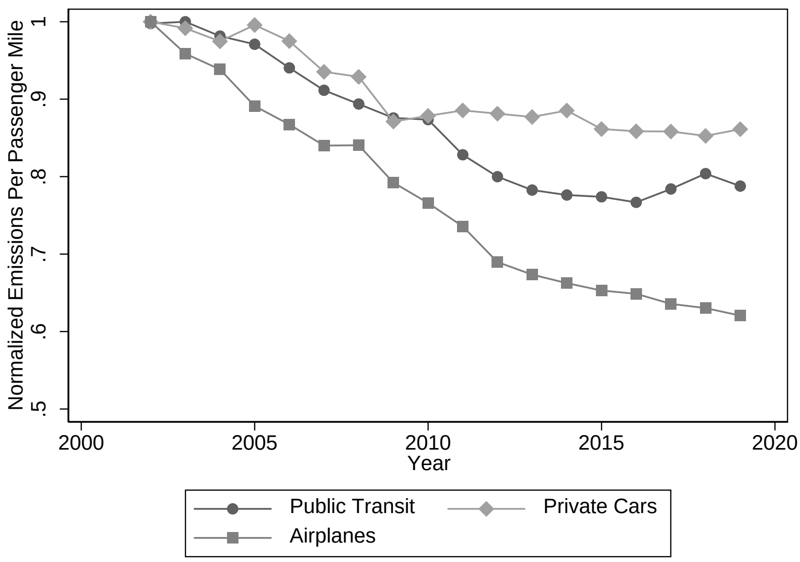


Figure 3B. Emissions Per Passenger Mile by Sector



Notes: Public transit's emissions per vehicle and passenger mile are calculated using emissions and mileage data from our NTD dataset. They are the weighted average efficiency of all directly operated vehicles. Emissions per vehicle mile of private cars are calculated using the US car fuel economy data. We use the inverse of average mile per gallon as an estimation of emissions per vehicle mile. For private cars' emissions per passenger mile, we divide total fuel consumption of private vehicles by total car passenger miles. To calculate the efficiency of aviation, we divide total fuel consumption of airplanes by total air vehicle and passenger miles each year. We assume each gallon of fuels produce the same amount of carbon emissions each year. The efficiency data are then normalized, with the maximum emissions per mile for each sector as 1.

Figure 4A. Average Public Transit Emissions Per Vehicle Mile in the US

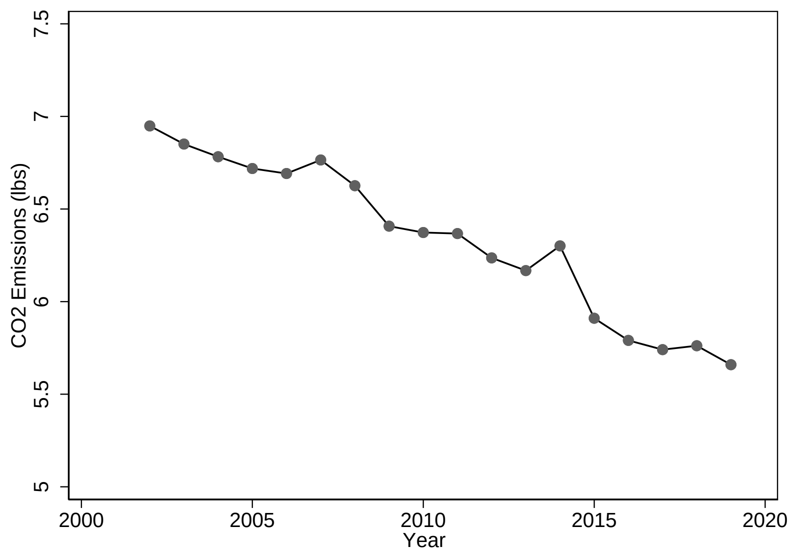
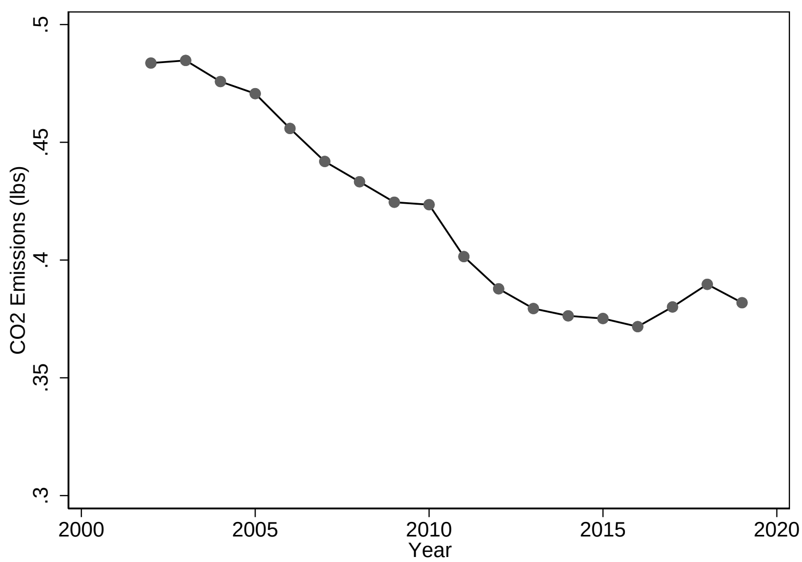


Figure 4B. Average Public Transit Emissions Per Passenger Mile in the US



Notes: These two figures show the efficiency trends of all directly operated public vehicles in the US. We exclude purchased transportation because those vehicles are operated and maintained by private transportation providers, not public transit agencies. We calculate emissions per vehicle mile and per passenger miles for each agency/year/mode/service unit of observation. When we calculate the average efficiency, figure 4A is weighted by the vehicle miles of the respective unit and figure 4B on the passenger miles.

Figure 5A. Average Public Transit Emissions Per Vehicle Mile in the Largest Cities

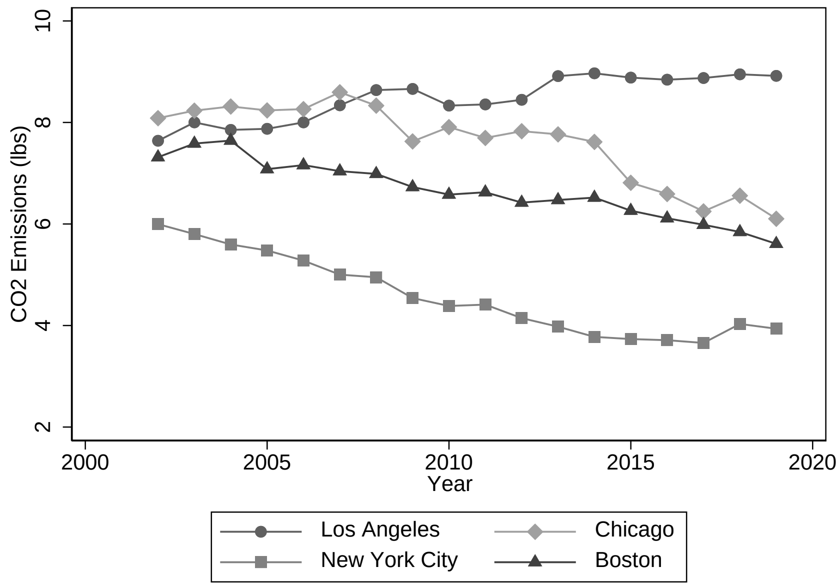
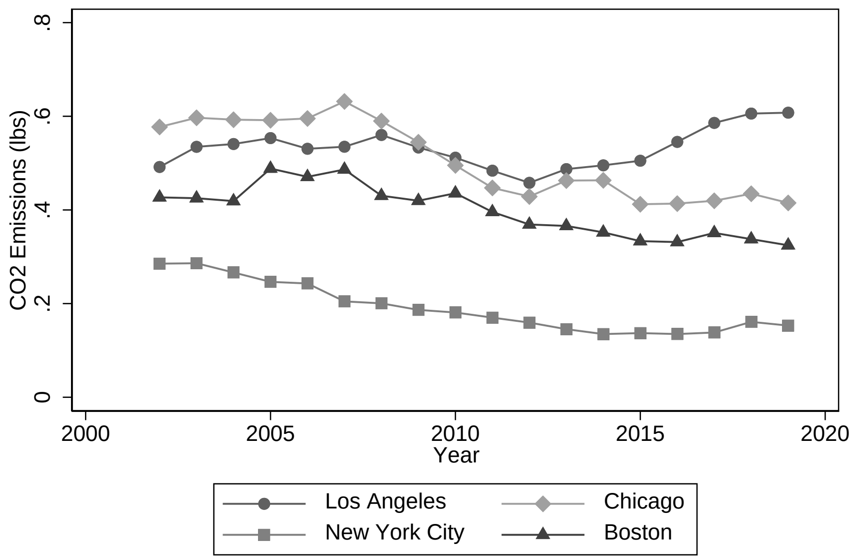


Figure 5B. Average Public Transit Emissions Per Passenger Mile in the Largest Cities



Notes: For the sake of cross-city comparisons, we only include directly operated buses and subways when calculating carbon efficiency because all the four cities have these two transit modes. Emissions per vehicle and passenger mile are weighted averages calculated in the same way as in figure 4. Los Angeles refers to the Los Angeles County Metropolitan Transportation Authority. Chicago refers to Chicago Transit Authority. New York City refers to MTA New York City Transit. Boston refers to Massachusetts Bay Transportation Authority.

Figure 6A. Percentage of Passenger Miles Travelled on Each Mode

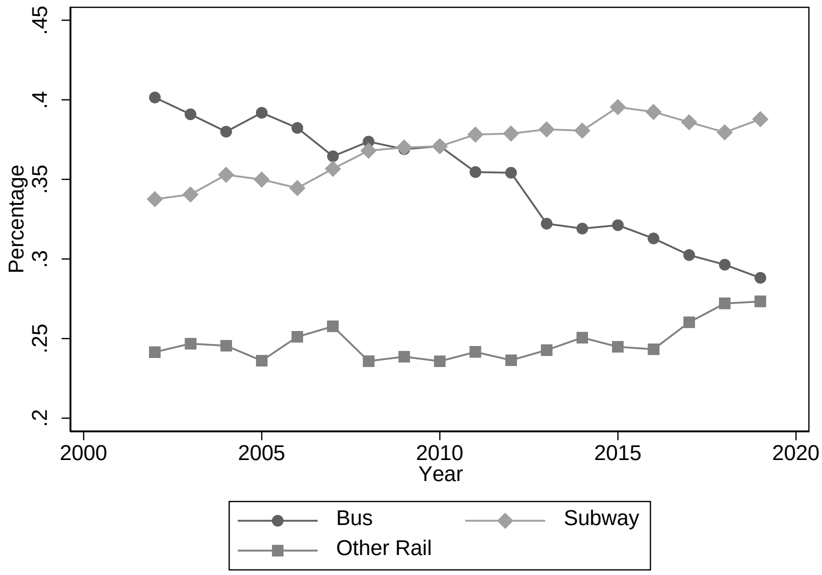
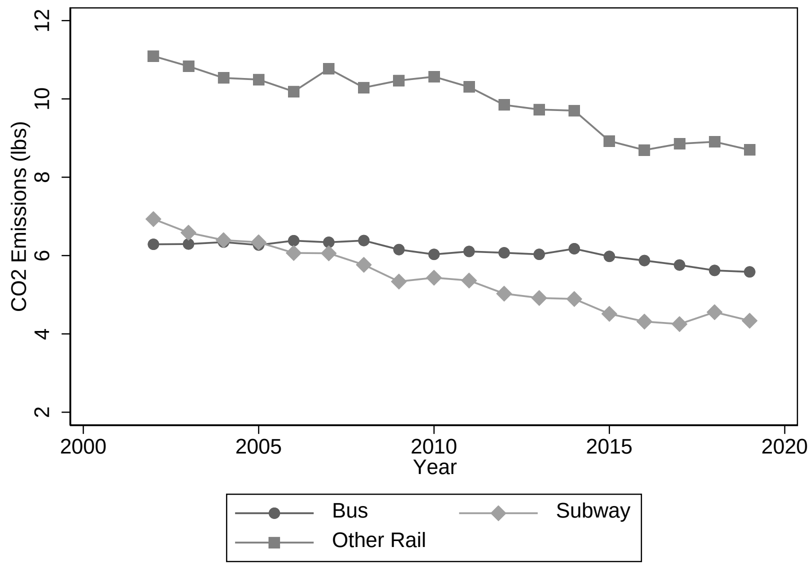


Figure 6B. CO_2 Emissions Per Vehicle Mile by Mode



Notes: Bus in this figure only includes regular buses, not including commuter buses or rapid transit buses. Subway refers to the heavy rail transit mode in the NTD dataset. Other rail includes commuter rail, light rail, and hybrid rail. As with the previous graphs, we only consider directly operated vehicles here. The percentage of passenger miles by each mode is calculated by dividing the total passenger miles of the mode by the total passenger miles of all public transit vehicles. Emissions per vehicle mile are the weighted averages (weighted by vehicle miles) of the efficiency of all services of a given mode.

Figure 7A. The Effects of Subsidies on the Pollution Externality

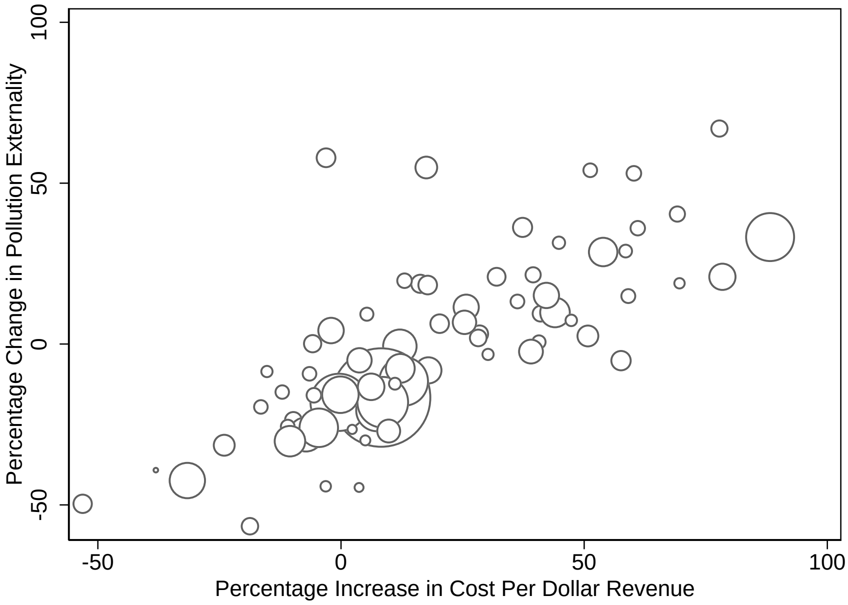
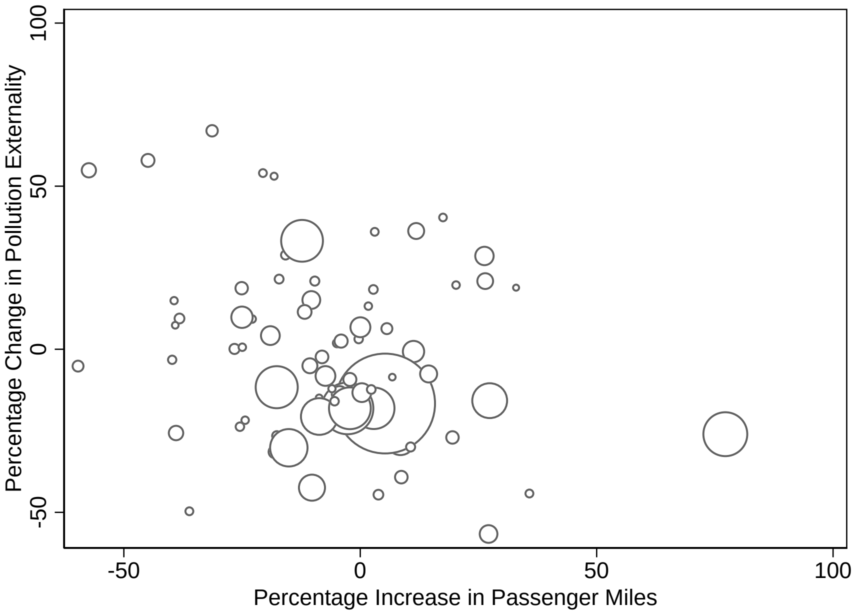


Figure 7B. The Effects of Total Passenger Miles on the Pollution Externality



Notes: In both figures, each dot represents one of the largest 75 public transit agencies (ranked by passenger miles in 2010) in the US. The size of the dots is proportional to the agency's total vehicle miles in 2010 in Figure 7A and proportional to total passenger miles in Figure 7B. Externalities refer to the social costs of carbon emissions associated with each dollar of revenue. The measure of an agency's cost-effectiveness is the operating cost associated with each dollar of revenue. Passenger miles refer to the sum of passenger miles across all transit modes in an agency. The increase and decrease are calculated based on the change from 2010 to 2019.

Table 1

Time Trends of Public Transit Vehicle Efficiency

	(1)	(2)	(3)	(4)
		log(Emissions/Mile)		
	Mile=VRM	Mile=PMT	Mile=VRM	Mile=PMT
Trend Before 2010	-0.0118*	-0.0176**		
	(0.00604)	(0.00795)		
Trend Since 2010	-0.0145***	-0.0168***		
	(0.00171)	(0.00152)		
Trend			0.00406	0.00638
			(0.00546)	(0.00706)
log(Ridership)	0.0311	-0.963***	0.148***	-0.891***
	(0.0662)	(0.114)	(0.0268)	(0.0314)
Public			0.159**	0.179**
			(0.0634)	(0.0782)
Trend x Public			-0.0117**	-0.0146**
			(0.00526)	(0.00711)
Constant	1.799***	1.888***	1.340***	1.433***
	(0.192)	(0.356)	(0.0888)	(0.114)
Observations	4843	4843	3478	3478
Agency Fixed Effects	Yes	Yes	Yes	Yes
R-squared	0.913	0.972	0.838	0.940
Sample	Directly Operated Vehicles		All Buses since 2008	

Cluster-robust standard errors at the agency level in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Notes: All regressions are estimated using OLS. Columns (1) and (3) are weighted by vehicle miles. Columns (2) and (4) are weighted by passenger miles. The unit of analysis is agency/year. VRM represents vehicle miles and PMT represents passenger miles. Ridership refers to passenger miles divided by vehicle miles. In columns (1) and (2), trend before 2010 equals year-2002, and trend after 2010 equals year-2010. The trend in columns (3) and (4) equals year-2008 because purchased transportation data are available only since 2008. The public dummy equals 1 if the vehicle is directly operated by the public transit agency, 0 if it belongs to purchased transportation. Emissions per mile in columns (1) and (2) are the weighted average efficiency across all modes within an agency. Columns (3) and (4) are estimated on buses from both direct operation and purchased transportation. We exclude other transit modes in these two models because bus is the only mode available both for direct operation and purchased transportation for most agencies.

Table 2

Percentage of Vehicle Miles Travelled by Energy Source

Energy Source	Service	2012	2019	Change
Diesel	DO	63.72%	58.02%	-5.7%
	PT	51.25%	53.62%	+2.37%
Hybrid Diesel	DO	6.86%	15.21%	+8.35%
	PT	3.18%	6.77%	+3.59%
Gasoline	DO	1.18%	1,95%	+0.77%
	PT	5.11%	6.9%	+1.79%
Hybrid Gasoline	DO	0.32%	0.39%	+0.07%
	PT	0.008%	0.04%	+0.03%
Compressed Natural Gas	DO	13.95%	24.02%	+10.07%
	PT	23.22%	31.65%	+8.43%
Liquified Petroleum Gas	DO	0.03%	0.08%	+0.05%
	PT	1.54%	0.64%	-0.9%
Electricity	DO	0.02%	0.25%	+0.23%
	PT	0.02%	0.38%	+0.36%

Notes: DO refers to direct operation, and PT refers to purchased transportation. We sum up the total vehicle miles by all buses of each service type in 2012 and 2019 respectively. We then sum up the vehicle miles by energy source and service type in these two years. We divide vehicle miles by each energy source by the total vehicle miles to get the percentage in a certain year. The electricity category includes both electric propulsion and electric battery buses. In 2012, 9.26% of public bus miles and 15.63% of privatized bus miles were run on biodiesel, but biodiesel is not reported in the 2019 inventory data.

Table 3

Bus Emissions as a Function of Model Vintage and Make Effects

	(1)	(2)	(3)	(4)
		log(CO_2 Emissions)		
log(Total Miles)	1.070***	1.066***	1.046***	1.037***
	(0.0102)	(0.00999)	(0.0163)	(0.0161)
log(Total Miles) x Year2019	-0.0599***	-0.0612***	-0.0109	-0.0130
	(0.0190)	(0.0190)	(0.0194)	(0.0192)
Year2019	0.932***	0.939***	0.302	0.306
	(0.267)	(0.266)	(0.273)	(0.270)
% Miles by Bus from 1991 to 1995	-1.819	-1.789	-1.603	-1.790
	(1.132)	(1.119)	(1.177)	(1.186)
% Miles by Bus from 1996 to 2000	-1.640**	-1.590**	-1.231	-1.302
	(0.796)	(0.803)	(0.849)	(0.882)
% Miles by Bus from 2001 to 2005	-1.684**	-1.644**	-1.341	-1.443*
	(0.782)	(0.792)	(0.822)	(0.858)
% Miles by Bus from 2006 to 2010	-1.730**	-1.675**	-1.531*	-1.617*
	(0.770)	(0.784)	(0.804)	(0.845)
% Miles by Bus from 2011 to 2015	-1.799**	-1.733**	-1.664**	-1.732**
	(0.788)	(0.802)	(0.814)	(0.856)
% Miles by Bus from 2016 to 2019	-1.735**	-1.703**	-1.577*	-1.677**
	(0.760)	(0.762)	(0.807)	(0.843)
% Miles by New Flyer Bus		0.170***		0.238***
		(0.0385)		(0.0502)
% Miles by Gillig Corporation Bus		0.0465		0.131***
		(0.0371)		(0.0429)
Public			0.189***	0.146**
			(0.0650)	(0.0578)
Constant	2.321***	2.289***	2.211***	2.378***
	(0.776)	(0.785)	(0.803)	(0.845)
Observations	483	483	584	584
R-squared	0.974	0.975	0.966	0.967

Cluster-robust standard errors at the agency level in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Notes: These regressions are estimated using OLS with cross-sectional data from 2012 and 2019. All models are unweighted. The unit of observation is agency/year/service type. Service type can be direct operation or purchased transportation. Miles are vehicle miles in this table. The omitted year category is year 2012. Buses from a certain period refer to those manufactured in the given time period. The omitted category is the percentage of miles driven by buses manufactured before 1990. The omitted bus type is other (not manufactured by New Flyer or Gillig Corporation). Columns (1) and (2) only include directly operated buses. The public dummy in columns (3) and (4) equals 1 if the bus is directly operated.

Table 4

The Cross-Sectional Determinants of Transport Emissions

	(1)	(2)	(3) Dummy=1 if the agency has at least one electric bus in 2019	(4) Dummy=1 if the school district has at least one electric bus in 2020
	log(Emissions/PMT)			
Republican Votes %	1.881***	0.638	-2.346	-1.681***
	(0.515)	(0.549)	(1.622)	(0.165)
College Graduates %	-1.930***	-1.770***	4.799***	1.338***
	(0.722)	(0.589)	(1.698)	(0.271)
log(Population)	-0.0588	-0.136***	0.354**	0.495***
	(0.0445)	(0.0439)	(0.149)	(0.0238)
Constant	0.244	1.291**	-6.709***	-8.193***
	(0.664)	(0.621)	(2.437)	(0.354)
Observations	4826	4826	234	11352
Year Fixed Effects	Yes	Yes	No	No
Region Fixed Effects	No	Yes	No	No
R-squared	0.541	0.669		

Cluster-robust standard errors at the agency level in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Notes: Columns (1) and (2) are OLS regression. Columns (3) and (4) are logistic regressions. The unit of analysis in columns (1) and (2) is agency/year. These two columns include all services directly operated by the public transit agencies from 2002 to 2019. They are weighted by passenger miles. Column (3) uses cross-sectional data on the largest 270 agencies in 2019. Column (4) uses cross-sectional data on all school districts in 2020. Column (3) is weighted by vehicle miles and column (4) by the number of students in the school district. In columns (1) and (2), emissions per refer to the weighted average efficiency across all modes within an agency. The three variables of interest are at the county-level. Republican votes data are from the 2020 election. College graduate percentage is the percentage of adults over 25 years old who have a bachelor degree in 2019. The population data are from 2019 as well. Four regions included in the region fixed effects are Northeast, Midwest, South, and West. In columns (3) and (4), the dependent variable is a dummy that equals 1 if a transit agency or school district owns electric buses in 2019 and in 2020 respectively. Some school districts contain multiple counties. We use the election, education, and population data from the largest county inside the district.

Table 5

"Green Accounting" for the Largest Transit Agencies

Agency	Year	Vehicle Miles (millions)	Passenger Miles (millions)	Operating Cost Per $ Revenue (in 1983 dollars)	Social Cost Per $ Revenue (in 1983 dollars)	Emissions Per Vehicle Mile (lbs)	Emissions Per Passenger Mile (lbs)
Massachusetts Bay Transportation Authority	2002	78.1	1775.4	2.612	0.030	9.132	0.402
	2019	55.7	995.6	2.341	0.013	5.640	0.316
MTA New York City Transit	2002	463.0	9730.4	1.759	0.015	5.997	0.285
	2019	484.6	12151.7	1.792	0.007	4.018	0.160
MTA Metro-North Railroad	2002	56.4	2129.5	1.766	0.018	9.306	0.247
	2019	76.1	2034.5	1.662	0.010	6.020	0.225
New Jersey Transit Corporation	2002	135.3	2341.0	1.966	0.021	6.470	0.374
	2019	157.7	2993.8	2.051	0.021	7.685	0.405
MTA Long Island Rail Road	2002	65.4	2094.1	2.224	0.019	8.633	0.270
	2019	75.7	3929.9	1.960	0.011	6.371	0.123
Southeastern Pennsylvania Transportation Authority	2002	81.5	1322.6	2.246	0.033	11.039	0.680
	2019	89.1	1412.1	2.743	0.024	7.411	0.468
Washington Metropolitan Area Transit Authority	2002	101.1	1889.1	2.149	0.028	8.839	0.473
	2019	135.0	1672.0	2.806	0.022	6.217	0.502
Maryland Transit Administration	2002	30.5	382.5	3.586	0.043	8.153	0.650
	2019	32.4	323.1	7.606	0.057	6.491	0.652
Metropolitan Atlanta Rapid Transit Authority	2002	58.8	816.7	2.977	0.059	8.448	0.609
	2019	55.3	693.8	3.492	0.034	4.759	0.379
Miami-Dade Transit	2002	39.1	386.3	3.494	0.055	7.705	0.781
	2019	40.7	387.6	6.057	0.054	6.282	0.659
Chicago Transit Authority	2002	128.7	1803.2	2.398	0.032	8.085	0.577
	2019	133.3	1959.9	2.459	0.023	6.103	0.415
Northeast Illinois Regional Commuter Railroad Corporation	2002	39.7	1534.3	2.225	0.044	17.948	0.464
	2019	46.7	1365.1	2.137	0.030	14.240	0.487
Metropolitan Transit Authority of Harris County, Texas	2002	45.1	450.1	4.769	0.080	6.501	0.651
	2019	54.4	483.5	8.400	0.081	4.789	0.539
San Francisco Bay Area Rapid Transit District	2002	60.0	1176.3	1.713	0.021	5.782	0.295
	2019	81.3	1771.6	1.395	0.010	3.405	0.156
Los Angeles County Metropolitan Transportation Authority	2002	107.9	1815.0	3.556	0.042	7.815	0.465
	2019	105.4	1760.3	7.077	0.058	8.583	0.514

Notes: The 15 largest agencies are chosen based on the rank of passenger miles in 2010. Vehicle and passenger miles are the total mileages of all transit modes from a certain agency. The real operating costs, revenues, and social costs are adjusted using CPI from the year 1983. The two efficiency variables are the weighted averages of all modes within an agency in a certain year. Emissions per vehicle mile are weighted on each mode's vehicle miles and emissions per passenger mile on passenger miles.