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 the social cost of 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 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. The composition of these emissions changed over time. As Los Angeles Metro opened new rail transit, rail emissions rose by 15% in the past two decades, while those from buses increased by less than 5%.

In late 2022, the Biden Administration enacted the Inflation Reduction Act. This legislation authorizes enormous new "green energy" subsidies. Going forward, urban transit agencies will have access to new funds to decarbonize their bus fleets and to reduce their carbon emissions from electricity consumption as the power grid's carbon footprint shrinks. We document that U.S have major cities have made slow progress in the recent past in shrinking their transport carbon emissions.

We measure the externality produced as a byproduct of local government activity.[4] We decompose carbon emissions production into 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, transit fleet composition (i.e. buses, light rail, heavy

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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

rail), and technique factors (e.g. age of the bus fleet, the emissions intensity of the electricity grid). We study the emissions reductions brought by shifts between transit modes, transitions to cleaner and more efficient electric grid, and the use of newer and cleaner durables (Baum-Snow and Kahn 2005; Holland et al. 2016; Li, Kahn, and Nickelsburg 2015). We document differences in efficiency progress 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.

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 increasing. Our findings build on past work benchmarking national transport energy efficiency in other countries and works studying the determinants of the U.S private fleet's efficiency dynamics (Ziolkowska and Ziolkowski 2015; 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 over the years 2002 to 2019 to test several hypotheses related to the environmental performance of different transit agencies. Our measure of environmental performance is a transit agency's 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 flatten 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. Most of them have decreasing emissions per mile.

Transit agencies face soft budget constraints as such agencies receive state and federal transfers. In this case, increases in gas prices may have smaller effects on increasing the public sector fleet's energy efficiency (Li, Kahn, and Nickelsburg 2015). On the other hand, 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.[5] The Post Office claimed that access to finance has been the main

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

obstacle slowing down electrification. 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.

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 richer, more progressive, and larger cities feature lower carbon emissions per mile. These cities are also more likely to adopt 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. We build on past works such as Winston and Langer (2006) that study the congestion externalities brought by public transit. Most U.S transit agencies lose money each year. 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. 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, we document a negative correlation between transit agencies' operating losses and energy efficiency gains. If an agency saves on its operating expenditure, it can spend more on capital upgrades. We also find evidence of economies of scale in emission reductions as the largest transit agencies outperform smaller agencies in reducing pollution.

This paper is organized as follows. We start by discussing the incentives of a given transit agency to reduce its greenhouse gas emissions externality. We then present our transport carbon emissions accounting framework and introduce our main data sources. Using our data, we compare the emission rates of US public transit with Europe public transit and US private transit. We move on to quantify the emissions time trend of US public transit and decompose it to composition and technique effects. We examine the cross-sectional heterogenies of public transit emissions across the nation. In the final section, we study the economies of scale and the role of subsidies in mitigating transit agencies' pollution externalities.

An Urban Transit Agency's Incentive to Decarbonize

In this section, we model a public transit agency's decision to reduce its greenhouse gas emissions per mile of service supplied. Only the largest transit systems feature heavy and light rail. This means that most transit agencies' emissions are produced by the bus fleet. Such a fleet is a mixture of older and new buses. At a cost, the transit agency can reduce its emissions rate by replacing diesel buses with energy-efficient ones powered by natural gas or electricity. While transit agencies do not have a direct incentive to internalize the social cost of their carbon emissions, they reduce their fuel expenditure when overall energy efficiency increases. Electric buses are more expensive than fossil fuel buses but transit agencies have access to state and federal funds that help to subsidize such capital replacement costs.[6]

Public transit agencies are non-profits that supply basic transit services that mainly benefit lower income people and create public sector jobs (Glaeser, Kahn and Rappaport 2008; Jerch, Kahn and Li 2017). These agencies face two separate budget constraints: an operating budget and a capital investment budget. Labor costs and fleet maintenance costs account for over 80% of their operating costs. Less than 5% of the total operating costs are fuel expenditure. Almost all transit agencies make an operating loss and have to rely on subsidies to balance their budgets.[7] State and local governments make large transfers to compensate local transit agencies' operating losses. Transit agencies are not free to allocate these subsidies to operation versus capital investments. Some of local subsidies and most of federal transfers are set aside exclusively for capital upgrades such as bus acquisition.

To explore how soft budget constraints affect the incentives of a non-profit agency, we explore the optimization problem of a representative agency that faces a hard constraint versus a soft budget constraint. If a transit agency faced a hard budget constraint (i.e. no subsidies), the optimization problem could be written as:

$$max_{L,F}\ S(L,F) \quad s.t.\ wL + pF \leq B \tag{1}$$

where S denotes the service level, L denotes labor, F denotes fuel consumption, w is the wage, p is the energy price, and B is the budget. S is an increasing function of L and F. Given this hard budget constraint, an increase in energy prices will induce a substitution effect so that transit agencies will engage in fuel conservation. They are thus incentivized to purchase more

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[6] For example, LA metro's capital investment projects including rail expansion and zero-emission bus purchases are completely funded by government transfers. This is also true for most other transit agencies.

[7] MTA in NYC and LA metro's operating revenues (mostly from passenger fares) cover roughly 20% of their total operating costs. The other 80% are subsidized. Among the largest 270 US public transit agencies, only 2 made positive operating profits when government subsidies are not considered.

efficient buses.

Now consider an agency that faces a soft budget constraint (Kornai, Maskin, and Roland 2003). This agency can ask for more funding if it goes over the initial budget. There is a σ probability that the government will provide G dollars of additional financial aids. In this case, when energy prices rise from p to p', the agency may keep the fuel consumption level at F (i.e. no conservation). It does so if the expected loss is zero or negative. That is, $(p' - p)F \leq \sigma G$. This implies that a softer budget (σ) or larger transfers (G) could disincentivize transit agencies from decarbonizing.

On the other hand, transit decarbonization could be accelerated when the capital investment budget is softened. US public transit agencies are mandated to comply with the Buy American Act. This requires the purchased buses, or at least 65% of their subcomponents (based on costs), to be manufactured in the US.[8] This Act prevents transit agencies from purchasing cheaper electric buses manufactured in Asia. Transit agencies are not likely to make such investments in the absence of external financial assistance. Government subsidies make the expensive domestic buses more affordable to transit agencies and this accelerates the bus replacement cycle (Li, Kahn, and Nickelsburg 2015). A transit agency's fuel efficiency is jointly determined by its soft operating budget and its soft capital budget.[9]

Throughout this section, we have abstracted from augmenting the objective of the transit agency to include a taste for voluntary restraint (Kotchen and Moore 2008; Kotchen 2013). In some progressive areas, the Mayor may intentionally appoint key agency employees who actively support environmental protection. Such managers of a non-profit may pursue their agenda of both supplying transit services but also prioritizing decarbonization.

A Carbon Emissions Accounting Framework for Evaluating Transit Agency Performance

[8] https://sgp.fas.org/crs/misc/IF10941.pdf

[9] Rebound effects have been documented in private transport (Gillingham, Rapson, and Wagner 2016). People drive more after opting into a more energy-efficient, high-quality vehicle. The upgrades of public transit buses may induce rebound effects as well. If more people substitute from driving to public transit due to these quality improvements, emissions per passenger mile would decline. However, emissions per vehicle mile could increase if these higher-quality buses bundle in additional features such as air conditioners. Total emissions from public transit hinge upon the scale versus the technique effects.

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.

$$Emissions_{jrt} = Kwh_{jrt} * f_{rt} + \sum_{l=1}^{n} fossil\ fuel_{jlt} * e_l \qquad (2)$$

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 from electricity generation, f_{rt}. 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 vehicle miles increase as the demand for public transit increases, electricity consumption and fossil fuel consumption will increase. A composition effect could occur if a transit agency builds a new rail system such as the light rail Exposition Line in Los Angeles (Baum-Snow and Kahn 2005). This line has enjoyed increased ridership as it has cannibalized bus rides. 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. In regions with clean electric grids, this composition shift lowers the emission rates of public transit (Holland et al. 2021).

Technique effects refer to the declines in the emission factors f and e. This could be a result of the greening of electric grids as more electricity is generated by renewables. These emission factors also vary with respect to the vintages of capital. Equation (2) can be rewritten so that "n" represents the set of fuel types and capital vintages. Newer buses have lower particulate matter emissions than older buses, yet they 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 2016). 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. [10] 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.[11] We merge the vehicle and passenger miles data into the NTD energy dataset by year, agency, mode, and service type. [12] 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.[13]

The fuel emission factors are from Environmental Protection Agency's (EPA) April 2021 data.[14] To calculate the total CO_2 emissions from fuel combustion, we multiply fuel consumption by its emission factor and sum them up (see equation (2)). The electricity emission factors are compiled from the summary reports of the Emissions & Generation Resource Integrated Database (eGRID).[15] The reports provide the electricity emission factor for each North American Electric Reliability Corporation (NERC) region.[16] 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 (2)). 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 from the NTD.[17] We obtain the

[10] https://www.transit.dot.gov/ntd/ntd-data
[11] https://ftis.org/urban_iNTD.aspx
[12] 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
[13] 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.
[14] https://www.epa.gov/climateleadership/ghg-emission-factors-hub
[15] https://www.epa.gov/egrid
[16] 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.
[17] https://www.transit.dot.gov/ntd/data-product/ts21-service-data-and-operating-expenses-time-series-mode-2

annual operating expenses and revenues for each agency/mode/service type. The pollution externality equals the amount of CO_2 emissions times the social cost of carbon. The green operating profit is total revenues minus the sum of operating costs and the pollution externality.

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.[18]

International Public Transit Comparisons

We compare bus emissions per vehicle mile and per passenger mile in the United States, the United Kingdom, and Germany. The UK bus emissions and mileage data are provided by the UK government.[19] The German bus mileage data is from the website of the Federal Statistical Office of Germany.[20] The bus emissions are calculated using data from the Federal Ministry of Transport and Digital Infrastructure of Germany.[21] We focus on buses because bus miles account for a large proportion of total public transit miles in all these three countries.[22]

Figure 1 shows 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 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

[18] 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 but not ridership). 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.

[19] 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

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

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

[22] 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.

decreased by 10.5% from 6.29 pounds/mile to 5.63 pounds/mile in. German buses achieved a 15.3% efficiency improvement from 4.32 pounds/mile to 3.66 pounds/mile.

The emissions per passenger mile show a similar pattern (not shown). 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 increase slightly from 0.67 pounds in 2002 to 0.7 pounds in 2019. This is mainly due to decreasing bus ridership in the US as a result of declining service quality and frequency (Taylor et al. 2009).

As shown by Figure 2, bus occupancy increased in Europe while it decreased in the US. In 2019, the ridership was 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, 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 US, and European 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 it.

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 3, we compare the efficiency gains of public transit with gains of private cars and aviation. Public transit's energy efficiency is calculated using our NTD dataset. Transit agencies from the NTD dataset only provide within-city transit. We supplement it with national-level Amtrak data provided by the Bureau of Transportation Statistics (BTS). Amtrak is a government-owned corporation that provides inter-city public transit. Energy efficiency data for private cars and airplanes are directly obtained or calculated from the BTS data.[23]

[23] 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

Figure 3A shows the normalized emissions per vehicle mile for each sector. Public transit and airplanes have similar efficiency gains (around 18%) from 2002 to 2019. 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. Despite the rapid innovations of road vehicles, urban transit agencies are slow in replacing deficient vehicles with cleaner ones. In contrast, private cars' efficiency increased by 32.3% from 2002 to 2019, nearly twice as large as that of public transit vehicles. Private car owners opt into high-efficiency vehicles to reduce the long-run fuel expenditure (Knittel 2011; Burke and Nishitateno 2013). Amtrak had the lowest fuel efficiency gains, and its emissions showed more fluctuations between years. Unlike a conventional urban transit agency, Amtrak faces an even softer operating budget constraint because it is directly run by the federal government. Its operating losses are always fully funded by tax dollars. This disincentivizes Amtrak from phasing out its deficient capitals as suggested by the mechanism in Section II. In absolute terms, airplanes produce the most pollution per mile travelled, and private vehicles are the most energy efficient. Amtrak's emissions per vehicle mile are roughly 15% more than urban public transit's.

Figure 3B plots the emission intensity as measured by emissions per passenger mile. Despite the significant decrease in emissions per vehicle mile, private cars have the smallest reduction in emissions per passenger mile (13.9%). 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 the aviation sector, the ridership increased by 31.7% in the past two decades. This has caused a sharp reduction in emissions per passenger mile. 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). Compared with the three other sectors, Amtrak's emissions per passenger mile have dropped the most, by almost 60%. Given that Amtrak's emissions per vehicle mile only decreased by 10% from 2002 to 2019 (see Figure 3A), such a significant drop in emissions per passenger mile was as a result of the increasing ridership.

Benchmarking US Public Transit's Efficiency Gains

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

Despite the greater efficiency gains by foreign public transit and domestic private transit, the US public transit exhibits a downward emission trend over time. Figure 4 graphs the normalized emissions per mile of all directly operated public transit services. Emissions per vehicle mile steadily trended down, dropping by 18.6% from 6.95 pounds in 2002 to 5.66 pounds in 2019. Multiple factors contribute to this improvement, 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. Most of the new rail riders are past bus riders who substitute. 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 (2)).

Emissions per passenger mile 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. The efficiency curve flattened after 2014. The ridership of public transit vehicles dropped by over 11% from 2014 to 2019. [24]

Based on the grapical evidence, we use regressions to study the national time trend of the energy efficiency of public transit agencies. We estimate the following regression for transit agency j in year t:

$$log(emissions\ per\ mile_{jt}) = \beta_0 + \beta_1{}'Trend + \beta_2\, log(ridership_{jt}) + \alpha_j + \varepsilon_{jt} \tag{3}$$

In equation (3), trend is a vector because we allow for a different time trend before and after 2010. This enables us to test whether the emissions mitigation accelerates due to recent innovations such as EVs and more government funding available to decarbonize the transit sector. 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

[24] We investigate the separate time trends for four of the largest public transit agencies: Los Angeles County Metropolitan Transportation Authority, Chicago Transit Authority, MTA New York City Transit, and Massachusetts Bay Transportation Authority in Boston. Their efficiency improvement trends 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.

control for agency-fixed effects (α_j). The standard errors are clustered at the agency level.

In Table 1, columns (1) and (2) report 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.[25] 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 shifts in transit mode composition. More passenger miles are travelled on cleaner modes. T-tests on the coefficients find no evidence that the emission reductions trend changed after 2010. In column (2), ridership is significantly negative as expected. Emissions per passenger mile are lower when there are more passengers on each vehicle.

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.

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[25] 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.

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:

$$log(\, emissions\, per\, mile_{jit}) = \beta_0 + \beta_1 trend_t + \beta_2\, log(\, ridership_{jit}) + \beta_3 public_i + \beta_4 trend \times public + \alpha_j + \varepsilon_{jit} \quad (4)$$

In equation (4), public is a dummy variable that equals 1 when the bus is directly operated. Other variables are defined as in equation (3). The standard errors are clustered at the agency level.

In both columns, the public dummy variable has significantly positive coefficients. Directly operated buses produce 15.9% more emissions per vehicle mile and 17.9% more per passenger mile on average. The negative coefficients of the interaction term show that directly operated buses have larger efficiency gains over time. The annual decline in public buses' 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 because agencies receive government subsidies to invest in new capitals. This is consistent with the mechanism from Section II. The unweighted average public bus fleet age is 8.24 years, and that of the private fleet is 7.42 years. 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.[26] More public miles are run on newer vehicles.

The trend variable has a positive yet statistically insignificant slope. We have no evidence that the emission rates of buses have been trending down. The negative coefficients of trend is the first two columns are likely due to efficiency improvements of other modes. The coefficients of the ridership variable are as expected in both columns. Buses with high ridership need to stop more often and for longer time at bus stops, reducing the overall fuel efficiency. Emissions per passenger mile decrease when there are more riders.

Emission Reductions from Mode Composition Shifts

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

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 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) document 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 5A shows the percentage of passenger miles on each mode over time. For buses, their share of total passenger miles decreased from 40.1% in 2002 to 28.8% in 2019. Subways and rails both had increasing shares. The subway's share rose 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 5B graphs the efficiency improvement rates across transit modes. 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. When we compare emissions per passenger mile of buses versus rails for the 10 largest transit agencies, they were on average 0.6 pounds and 0.3 pounds respectively in 2019.

The Rising Demand for Electric Buses

Given that the transportation sector produces a large share of U.S carbon emissions, there is simultaneously a private sector and a public sector push to 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 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, but 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.[27] The privatized bus fleets are cleaner overall, but the public bus fleets show more rapid transition to cleaner fuels.[28]

Notably, the mileage shares of directly operated electric buses increase from 0.02% to 0.25%. The twelvefold increase demonstrates the recent growth, but the overall share is still tiny because of the durability of public transit buses.[29] 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.[30] Transit agencies face the decision whether to swap their diesel buses for gas-powered buses or electric buses. Compared to gas-powered buses, electric buses have a high upfront price premium that outweighs their long-run savings on operating and energy costs (Holland et al. 2021). Although electric buses feature lower environmental costs, transit agencies may be more incentivized to purchase natural gas buses given their lower economic costs. This can explain the surge in the percentage miles travelled by CNG buses from 2012 to 2019.

The bus fleet electrification rate in the US is lower than other major economies such as the European Union and China.[31] Some barriers to bus electrification include the lack of

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[27] 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.

[28] 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.

[29] 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.

[30] https://www.rff.org/publications/issue-briefs/an-analysis-of-us-subsidies-for-electric-buses-and-freight-trucks/ The annual market share of electric buses is tiny in the US. 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.

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

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. Shielded from competition, these firms manufacture more expensive yet less efficient electric buses than their foreign counterparts (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.

The second impact of this bus substitution is to reduce PM2.5 emissions for those on the bus and those who walk by the road. Urban residents have traditionally been exposed to more pollution, even though they produce lower emissions (Carozzi and Roth 2023). Emissions per passenger mile decrease as more urban 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 larger negative externalities. Public health studies have quantified bus riders' and pedestrians' exposure to bus emissions. The concentration of pollutants such as PM2.5 is several times higher inside diesel buses than CNG buses (Sabin et al. 2005). 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). Transit emissions also have disproportionately 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 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.

statistics/charts/electric-bus-registrations-by-region-2015-2020

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.[32] 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.

$$log(\,total\ emissions_{jt}) = \beta_0 + \beta_1{}'Z + \beta_2{}'X_{vintage} + \beta_3{}'X_{make} + \varepsilon_{jt} \qquad (5)$$

In equation (5), Z is a covariate vector including mileage, year 2019 dummy, their interaction term, and a dummy of direct operation. $X_{vintage}$ is a vector of vintage dummies, and X_{make} is a vector of make dummies. 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 makes 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. The standard errors are clustered at the agency level.

Table 3 reports the results from equation (5). 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 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 negative coefficients show that buses manufactured later than 1990 generate fewer emissions than those before 1990. These coefficients mostly have increasing absolute values over time. 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 1.7%.

The coefficient on the public dummy is significantly positive. For public and privatized

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

bus fleets with the same age and make composition and driven the same distance, directly operated buses produce 14.6% to 18.9% more emissions than purchased transportation buses (see columns (3) and (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.[33] Private transit providers may purchase energy-efficient models with higher upfront costs. Therefore, at a given point in time, the private bus fleet generally produces less emission per mile, although we have previously documented that the public fleet features more rapid transition to clean energy over time. This is consistent with the results from Table 1. Public transit agencies have a soft capital budget constraint, which enables them to purchase expensive energy-efficient buses.

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 more emission-intensive 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. They have strong market power in the electric bus market due to the Buy American Act.

Unlike private transit providers, public transit agencies tend to purchase vehicles from large manufacturers because of the Buy American Act. 19.7% and 58.3% of the total mileage from directly operated buses is run on New Flyer and Gillig Corporation buses respectively. 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. They make the investment if the present discounted value of long-run savings on energy and operation costs outweighs the price premium of the energy-efficient vehicle models. Given this hard budget constraint, the high cost of zero-emission buses could hinder the substitution. Such substitutions lower the carbon footprint given that the "rebound effect" associated with public transit is likely to be low.

[33] 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/

Cross-Sectional Determinants of Public Transit Carbon Emissions

In previous sections, we have documented the national progress in public transit emissions reductions and decomposed the sources of these reductions. The national-level analysis does not capture the variations in public transit's energy efficiency across regions at a point in time. 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). One explanation for this 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 (Kotchen and Moore 2008; Costa and Kahn 2013).

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.[34] 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 transit agency j (located in county i) at time t:

$$log(emissions\ per\ mile_{jt}) = \beta_0 + \beta_1{}'X_j + \mu_t + \omega_j + \varepsilon_{jt} \quad (6)$$

In the above equation, X is a vector including Republican votes, college graduates, and population. 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 (8).

In both columns, Republican votes have a positive coefficient though insignificant when region fixed effects are included. 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

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

fixed effects. The college graduate variable's coefficient is negative and statistically significant. A 10% increase in the county's share of adults who are college graduates is associated with a 19% reduction in local carbon emissions from public transit (see column (1)).

Emissions per passenger mile are lower in cities with a larger population. When population rises by 10%, emissions per mile decline by 1.3% in column (2). The public transit ridership is higher in densely populated cities, whereas most people drive in sparsely populated cities. However, this numerically small coefficient suggests that only a tiny fraction of the population takes public transit even in large 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 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 to 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.[35] We estimate the following logistic regression specification 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).

$$P(Electric_i) = \frac{\exp(\beta' X_i)}{1+\exp(\beta' X_i)} \quad (7)$$

where electric is a dummy equal to 1 if the transit agency has electric buses in 2019 or if the school district has electric school buses in 2020.[36] X is a vector including the same covariates as in equation (6).

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

[36] 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.

The results are reported in columns (3) and (4) of Table 4. Electric bus 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's 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, statistically significant at the 1% level. The coefficient of Republican votes is negative but insignificant in column (3). We interpret this fact as the public and the private sector's different responses to local demand. Public transit agencies are heavily subsidized by the government. They can continue to operate even when demand drops. Approximately 1/3 of the school buses in the US are privatized. These private operators purchase more electric school buses in liberal regions due to the higher local demand for electric transit (Kahn 2007). By switching to electric buses, they also economize on energy expenditure to increase profits.

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. Without public transit, the private sector's negative externality would have been even larger. However, our previous analysis shows that the public transit sector still produces large amounts of emissions. Studies have found mixed results on whether public transit subsidies are welfare-improving (Shirley and Winston 1998; Parry and Small 2009). In this section, we measure the social cost of the public sector's transit service production in the absence of a Pigouvian Tax.

We use the costs and revenues data for each public transit agency from 2002 to 2019 to calculate its costs, revenues, and climate change externality associated with each dollar of revenue.[37] The externality is calculated using equation (2), and we translate this carbon emissions into a dollar value by multiplying by the social cost of carbon ($35).

Unlike private transit providers, public transit agencies are mandated to supply at least the regulated level of output (Williams 1979). This causes most US transit agencies to bear

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

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 revenues.[38] In 2002, an average agency spent $3.74 for $1 of revenue, and the median 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 a median agency spent $3.49. The loss went up because of the decreasing ridership and the pressure from worker unions that demand higher wages. The loss could decrease if transit agencies can accommodate commuters' demand for new routes and modes (e.g. more subways and fewer buses) and shut down unused capitals. Previous research has documented that transit agencies' capital investments are inefficient because they often concentrate on a few metro lines rather than bring systematic improvements (Taylor et al. 2009).

Although public transit agencies' loss went up, federal subsidies have incentivized more investments in energy-efficient capitals such as electric buses to mitigate the climate change externality. In 2002, transit agencies' each dollar of revenue was associated with 4.89 cents of climate change externality, and the median externality was 3.96 cents. 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 Figure 6A, we plot a histogram of the ratio between the social cost and the total cost in 2002 and 2019 respectively. Consistent with the quantitative evidence above, the average ratio dropped from 1.2% in 2002 to 0.75% in 2019. This pattern is evident for agencies in large cities such as New York City (0.9% to 0.43%), Los Angeles (1.2% to 0.86%), and Chicago (1.6% to 1.1%).

We use our estimates of the "green accounting" adjusted operating profits for the nation's 75 largest agencies to explore the relationship between an agency's pollution and its operating loss. Figure 6B reports that agencies with smaller operating loss also tend to have lower emissions per mile. Because transit agencies are non-profit organizations, they spend all money they get (i.e. operating revenue plus subsidies). If there are more riders, agencies make more revenues to cover their operating costs. In this case, they will have more funding left to upgrade their durable capitals. Energy efficient vehicles reduce both the operating and the social costs of transit service provision. Such declining marginal costs lead to increasing returns

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

to scale in pollution reductions. The graph shows that large agencies (mostly at the bottom left) overall make smaller losses and generate fewer emissions than do small agencies.

In Table 5, we list the statistics on mileage, operating loss, and pollution externalities of the fifteen largest transit agencies in the US (ranked by total passenger miles). 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 them made larger losses, but their average loss was smaller loss than an average agency. In 2019, for these largest agencies, each dollar of revenue was associated with $2.86 of spending, 38% lower than the national average. They also made more progress in pollution reduction, with eleven of them reducing their emissions per dollar revenue. In 2019, they produced an average of 2.2 cents of negative externality for each dollar of revenue, 55% lower than the national average. Urban transit agencies with high ridership tend to receive more government fundings for capital investments. This can accelerate their vehicle turnovers. These statistics corroborate the pattern in Figure 6B and again imply an economies of scale in emissions reduction.

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. Yet, 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 were 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.

References

Baum-Snow, Nathaniel, Matthew E. Kahn. "Effects of urban rail transit expansions: Evidence from sixteen cities, 1970-2000." *Brookings-Wharton papers on urban affairs* (2005): 147-206.

Behrentz, Eduardo, Lisa Sabin, Arthur Winer, Dennis Fitz, David Pankratz, Steven Colome, and Scott Fruin. “Relative Importance of School Bus-Related Microenvironments to Children’s Pollutant Exposure.” *Journal of the Air & Waste Management Association* (2005). 55. 1418-30. 10.1080/10473289.2005.10464739.

Burke, Paul J., and Shuhei Nishitateno. "Gasoline prices, gasoline consumption, and new-vehicle fuel economy: Evidence for a large sample of countries." *Energy Economics* 36 (2013): 363-370.

Carozzi, Felipe, and Sefi Roth. "Dirty density: Air quality and the density of American cities." *Journal of Environmental Economics and Management* 118 (2023): 102767.

Copeland, Brian, R., and M. Scott Taylor. "Trade, Growth, and the Environment." *Journal of Economic Literature*, 42, no. 1 (2004): 7-71.

Costa, Dora L., and Matthew E. Kahn. “Do liberal home owners consume less electricity? A test of the voluntary restraint hypothesis.” *Economics Letters* 119, no. 2 (2013): 210-212.

Davis, Lucas W., and Matthew E. Kahn. "International trade in used vehicles: The environmental consequences of NAFTA." *American Economic Journal: Economic Policy* 2, no. 4 (2010): 58-82.

Gillingham, Kenneth, David Rapson, and Gernot Wagner. “The Rebound Effect and Energy Efficiency Policy.” *Review of Environmental Economics and Policy* 10, no. 1 (2016): 68–88.

Glaeser, Edward L., and Matthew E. Kahn. "Sprawl and urban growth." In *Handbook of regional and urban economics*, vol. 4, pp. 2481-2527. Elsevier, 2004.

Glaeser, Edward L., Matthew E. Kahn, and Jordan Rappaport. "Why do the poor live in cities? The role of public transportation." *Journal of urban Economics* 63, no. 1 (2008): 1-24.

Holland, Stephen P., Erin T. Mansur, Nicholas Z. Muller, and Andrew J. Yates. “Are there environmental benefits from driving electric vehicles? The importance of local factors.” *American Economic Review* 106, no. 12 (2016): 3700-3729.

Holland, Stephen P., Erin T. Mansur, Nicholas Z. Muller, and Andrew J. Yates. “The Environmental Benefits of Transportation Electrification: Urban Buses.” *Energy Policy* 148 (2021): 111921. https://doi.org/10.1016/j.enpol.2020.111921.

Hu, Shishan, Suzanne E. Paulson, Scott Fruin, Kathleen Kozawa, Steve Mara, and Arthur M. Winer. “Observation of Elevated Air Pollutant Concentrations in a Residential Neighborhood of Los Angeles California Using a Mobile Platform.” *Atmospheric environment (Oxford, England: 1994)*, *51* (2012): 311–319. https://doi.org/10.1016/j.atmosenv.2011.12.055

Jerch, Rhiannon, Matthew E. Kahn, and Shanjun Li. “The efficiency of local government: The role of privatization and public sector unions.” *Journal of Public Economics* 154 (2017): 95-121.

Kahn, Matthew E. “Do greens drive Hummers or hybrids? Environmental ideology as a determinant of consumer choice.” *Journal of Environmental Economics and Management* 54, no. 2 (2007): 129-145.

Kahn, Matthew E. “New Evidence on Trends in Vehicle Emissions.” *The RAND Journal of Economics* 27, no. 1 (1996): 183–96. https://doi.org/10.2307/2555798.

Kahn, Matthew E., and Jerry Nickelsburg. “An economic analysis of us airline fuel economy dynamics from 1991 to 2015.” No. w22830. National Bureau of Economic Research, 2016.

Knittel, Christopher R. "Automobiles on steroids: Product attribute trade-offs and technological progress in the automobile sector." *American Economic Review* 101, no. 7 (2011): 3368-99.

Kornai, Janos, Eric Maskin, and Géard Roland. "Understanding the soft budget constraint." *Journal of economic literature* 41, no. 4 (2003): 1095-1136.

Kotchen, Matthew J. "Voluntary-and information-based approaches to environmental management: A public economics perspective." *Review of Environmental Economics and Policy* (2013).

Kotchen, Matthew J., and Michael R. Moore. "Conservation: From voluntary restraint to a voluntary price premium." *Environmental and Resource Economics* 40, no. 2 (2008): 195-215.

Li, Shanjun, Matthew E. Kahn, and Jerry Nickelsburg. “Public transit bus procurement: The role of energy prices, regulation and federal subsidies.” *Journal of Urban Economics* 87 (2015): 57-71.

Parry, Ian W. H., and Kenneth A. Small. "Should Urban Transit Subsidies Be Reduced?" *American Economic Review* 99, no. 3 (2009): 700-724.

Sabin, Lisa D., Eduardo Behrentz, Arthur M. Winer, Seong Jeong, Dennis R. Fitz, David V. Pankratz, Steven D. Colome, and Scott A. Fruin. “Characterizing the range of children's air pollutant exposure during school bus commutes.” *Journal of Exposure Science & Environmental Epidemiology* 15, 377–387 (2005). https://doi.org/10.1038/sj.jea.7500414

Shirley, Chad, and Clifford Winston. "Alternate Route: Toward Efficient Urban Transportation." (1998).

Small, Kenneth. "Road pricing and public transit: Unnoticed lessons from London." *Access* 26, no. 3 (2005): 10-15.

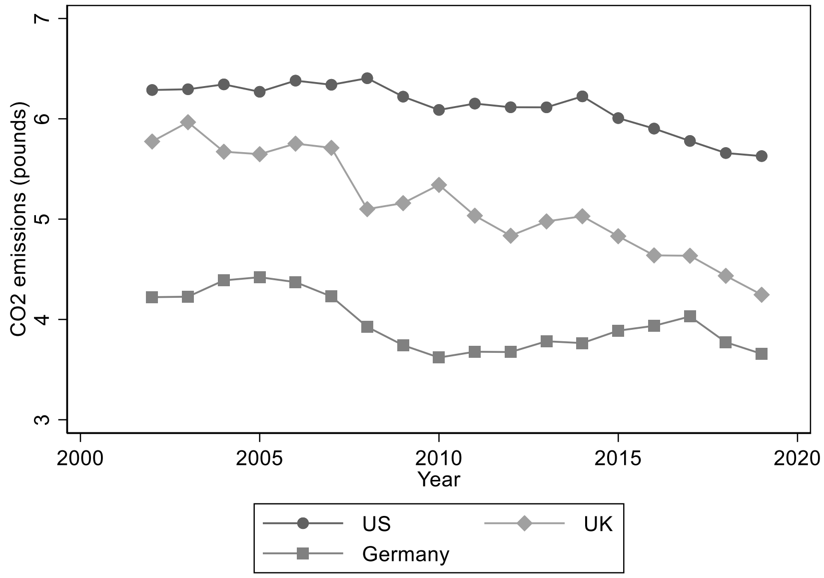
Taylor, Brian D., Douglas Miller, Hiroyuki Iseki, and Camille Fink. “Nature and/or Nurture? Analyzing the Determinants of Transit Ridership across US Urbanized Areas.” *Transportation Research Part A: Policy and Practice* 43, no. 1 (2009): 60–77. https://doi.org/10.1016/j.tra.2008.06.007.

Williams, Martin. “Firm size and operating costs in urban bus transportation.” *The journal of industrial economics* (1979): 209-218.

Winston, Clifford, and Ashley Langer. "The effect of government highway spending on road users' congestion costs." *Journal of urban Economics* 60, no. 3 (2006): 463-483.

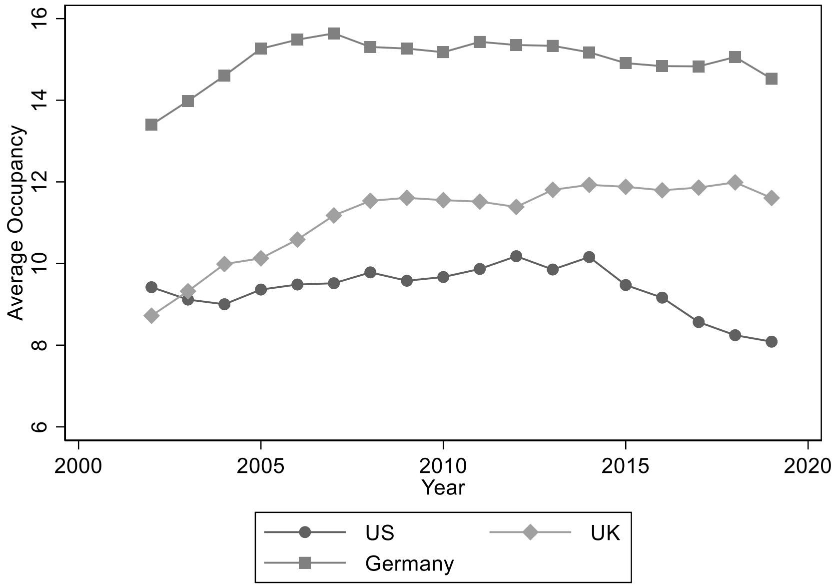
Ziolkowska, Jadwiga R., and Bozydar Ziolkowski. "Energy efficiency in the transport sector in the EU-27: A dynamic dematerialization analysis." *Energy Economics* 51 (2015): 21-30.

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



Notes: 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. We interpolate the vehicle and passenger miles of German buses in 2002 and 2003 because the data is available from 2004. In the UK and Germany, total mileage data is only available at 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

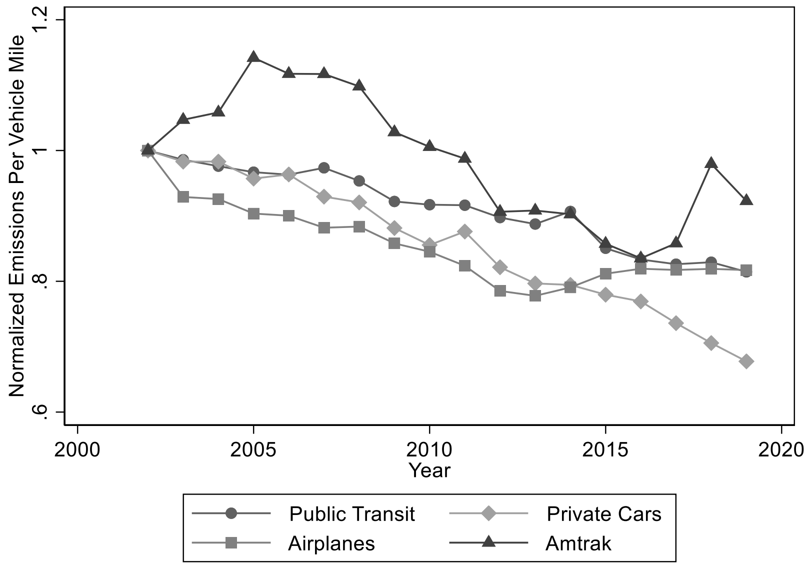
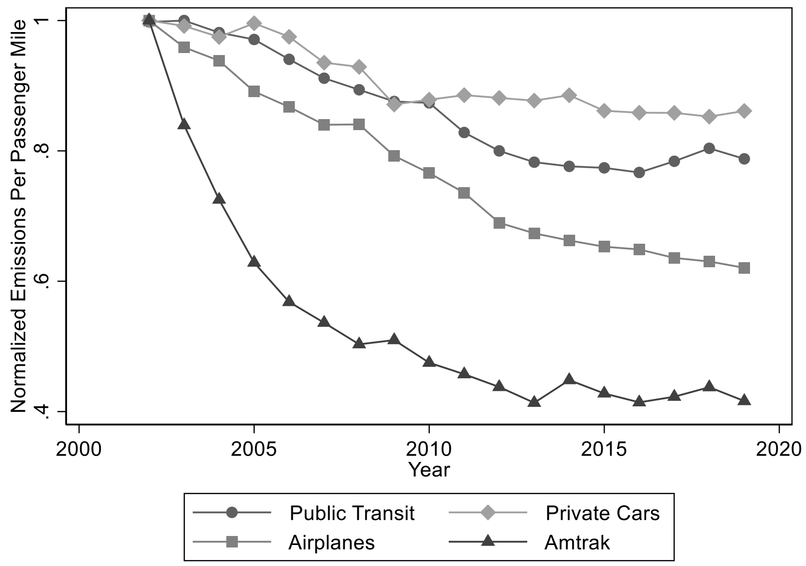
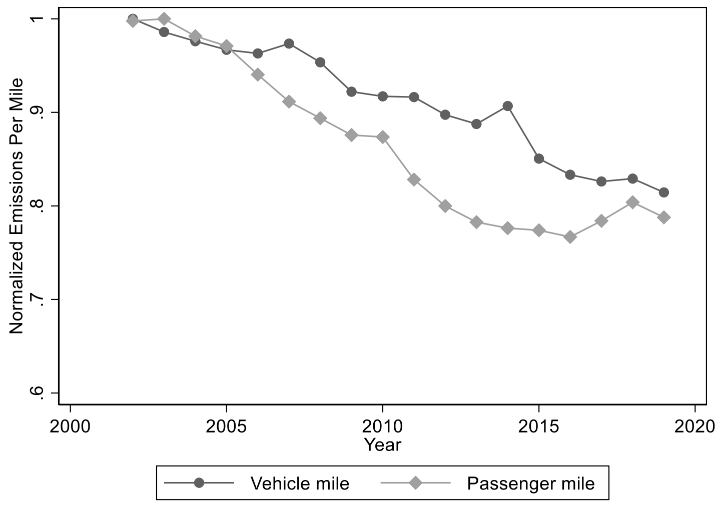


Figure 3B. Emissions Per Passenger Mile by Sector



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/mile for the other three modes are calculated using the annual fuel consumption and mileage data at the national level. We assume each gallon of fuels produce the same amount of carbon emissions over time, but each kWh of electricity does not.

Figure 4. Average U.S Public Transit Emissions Per Mile



Notes: This figure shows the efficiency trends of all directly operated public vehicles in the US. We exclude purchased transportation vehicles that are operated and maintained by private transportation providers. When we calculate the average efficiency, emissions/vehicle mile is weighted by the vehicle miles of the respective unit and emissions/passenger mile by the passenger miles.

Figure 5A. Percentage of Passenger Miles Traveled by Mode

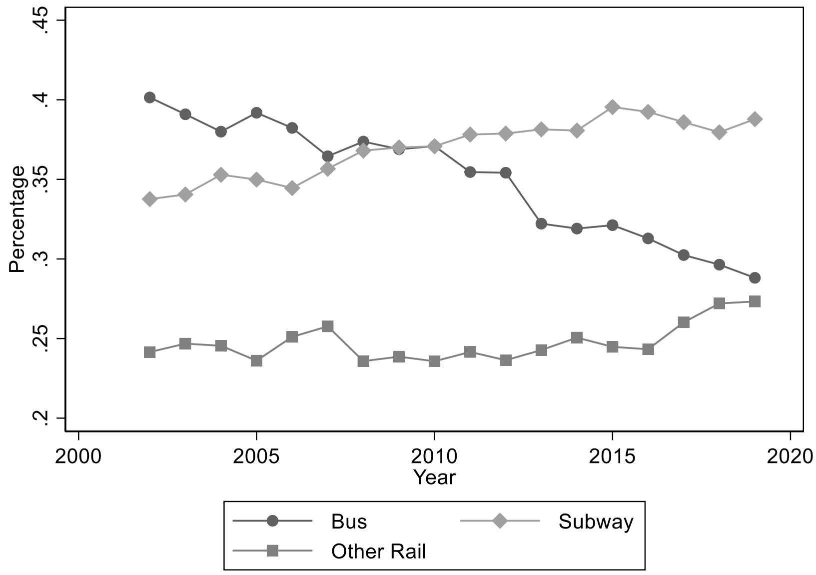
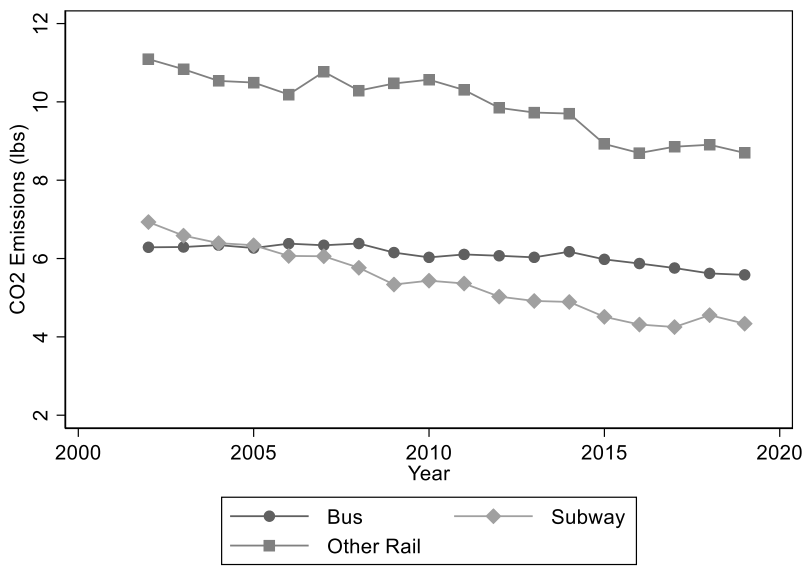


Figure 5B. CO_2 Emissions Per Vehicle Mile by Mode



Notes: Bus in this figure only includes regular buses, not 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. 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 6A. Transit Agencies' Private and Social Costs

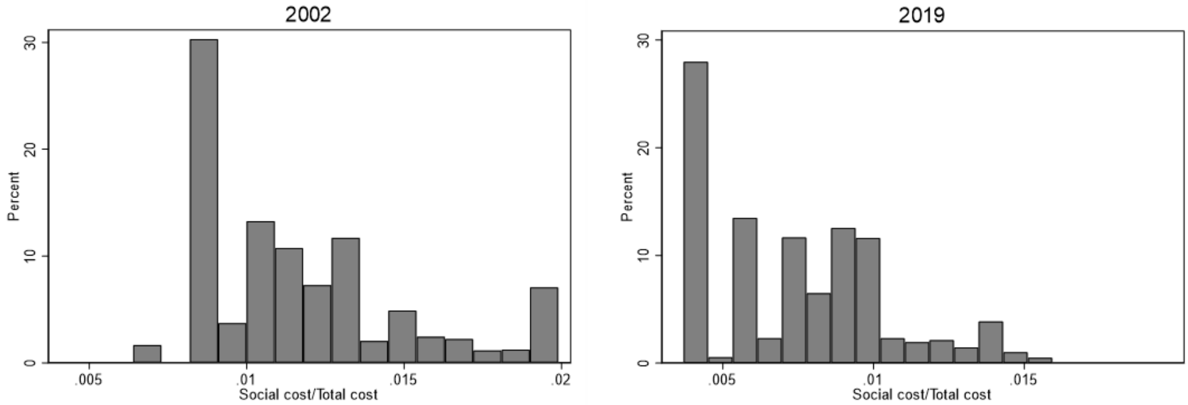
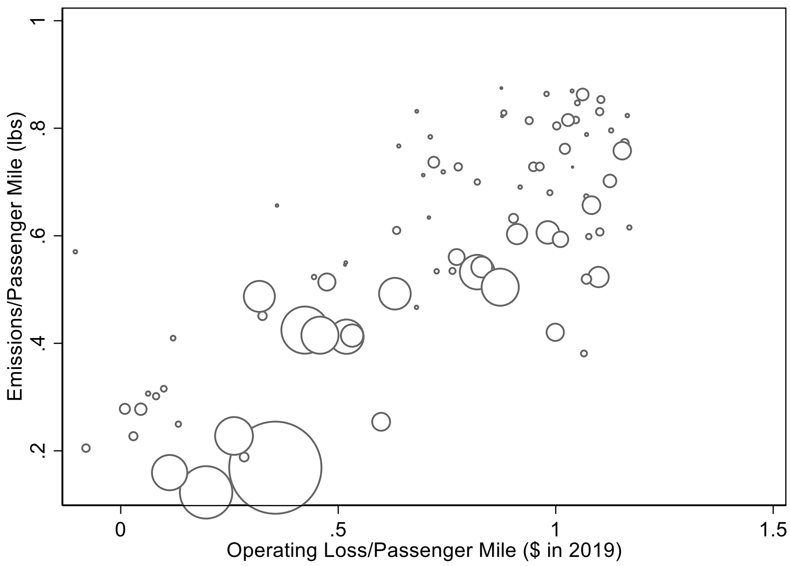


Figure 6B. The Relationship Between Operation Efficiency and Pollution Externality



Notes: In Figure 6A, total cost is the sum of the social cost from emissions and the private cost (i.e. operating cost). In the histogram, we weight the ratio by passenger miles. In Figure 6B, 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 passenger miles. Operating loss is the difference between the operating cost and the revenue.

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. The trend variable is a yearly time trend. 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. 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	Social Cost Per $ Revenue	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. Emissions per vehicle mile are weighted on each mode’s vehicle miles and emissions per passenger mile on passenger miles.