Carbon Intensity of Transit Modes in Boston and Phoenix

Matt Barnes, Jess Horowitz, & Karissa Wenger

1. Abstract

In light of the current need to limit CO_2 emissions, the use of public transportation is often presented as a favorable option to driving a personal automobile. However, limited work has been done to quantify the carbon emissions of different public transportation modes in comparison with automobiles. In this paper, the carbon emissions of public transportation systems in two cities, Boston and Phoenix, are compared using a common metric: carbon emissions per passenger-mile. It is determined that the carbon intensity of Boston's rapid bus and commuter rail is about 1.3 and 1.6 times higher, respectively, than an automobile, and the carbon intensities of all types of buses in Phoenix are about 1.4 to 1.7 times higher than an automobile. Several ways to improve the carbon intensity performance of these two systems are proposed, including increasing ridership, modernizing the systems, and electrifying the systems, and opportunities for further research and improvement of the analysis are discussed.

2. Introduction

In order to reach CO_2 emissions targets and limit global temperature rise, a portfolio of technologies and strategies is required. Transportation contributes to 28% of CO_2 emissions in the U.S., and promoting the use of public transportation is a common strategy to reduce transportation emissions.[27] Although it is assumed and generally accepted that utilizing public transportation will reduce an individual's carbon footprint, limited work has been done to quantify the carbon emissions of different public transportation modes. Thus, we developed a common metric to calculate the emissions intensity of public transit and examined how this intensity varies between transit modes and cities. We also determined what shift in public transportation ridership would be needed to impact emissions intensity.

We focused our analysis on two cities: Boston and Phoenix. There is a significant quantity of public transportation data available for these cities, and there are significant differences between their system sizes, ages, and physical locations, which we expected would lead to an informative comparison. We began by researching the current composition of these two public transit systems.

Phoenix

The Valley Metro, the public transportation agency in the Phoenix metro area, operates various bus services (e.g. commuter, local, express), streetcars, light rail, paratransit vehicles, and vanpools.[1] The system services 513 square miles and serves 19 communities, including the city of Phoenix.[1] The light rail, which is powered by electricity, opened in 2008 with 20 miles of rail and has since expanded to 28 miles.[2]

According to the U.S. Census, in 2020 there were 2,265,326 commuters in the Phoenix metro area over the age of 16.[3] They used the following commute options:[3]

Commute Method (2020)	% of Commuting Population
Car, truck, or van – drove alone	73.9
Car, truck, or van – carpooled	10.8
Public transportation (excluding taxicab)	1.7
Walked	1.5
Other Means	2.4
Worked from home	9.7

Table 1: Phoenix Metro Commuter Profile in the year 2020.[3]

As can be seen, only a small portion of the population used public transportation, while the majority of commuters drove alone.[3]

The Valley Metro fleet consisted of 939 buses in 2020.[4] While a detailed fleet summary for buses was not available, several Valley Metro publications formed the basis of the assumptions regarding fuel types for Valley Metro buses. For this evaluation, the Valley Metro is assumed to operate CNG, diesel, and diesel-hybrid buses in the following proportions:[5,6]

Bus Fuel Type	% of Fleet
CNG	73
Diesel	22
Diesel-Hybrid	5

Table 2: Valley Metro Bus Fleet Makeup by Vehicle Fuel Types in 2020.[5,6]

Boston

The Massachusetts Bay Transportation Authority (MBTA), who manages public transit in the Greater Boston Area, operates 5 light rail lines, 13 commuter rail lines, 170 bus routes, 4 trolley buses, 1 rapid bus, a ferry, and The Ride (a vanpool).[12] The light rail and trolley buses are powered by electricity, while the commuter rail, buses, and rapid buses are diesel-powered.[16] The system covers 3,244 square miles.[13]

According to the U.S. Census, the 375,912 commuters in Boston over the age of 16 in 2020 used the commute options shown:[14]

Commute Method	% of Commuting Population
Car, truck, or van – drove alone	37.5
Car, truck, or van – carpooled	10.8
Public transportation (excluding taxicab)	30.7
Walked	14.6
Other Means	4.0
Worked from home	7.3

Table 3: Boston Commuter Profile in the year 2020.[14]

As can be seen, a significant portion of Boston' commuters use public transit.[14]

3. Methods

Using publicly available sources, such as the Federal Transit Administration's (FTA) National Transportation Database (NTD), we collected data and calculated the emissions intensities of the public transportation modes in each city on a kg CO_2/person-mile basis. For Boston, we did not calculate the emissions associated with the ferry and The Ride, since these two types of public transit make up only 0.3% and 0.2% of the total MBTA ridership per year.[12]

3.1 Light Rail in Phoenix

According the the NTD, the Valley Metro Rail used 23,474,521 kwh of electricity in 2020.[7] The Valley Metro also reported 3,401,452 vehicle miles traveled (VMT) and 90,553,779 passenger miles traveled (PMT) in 2020.[8]

Light rail emissions were quantified by using an emissions factor for the average CO-$_2$ emissions per KWh in 2020 for Arizona, as defined by the EIA. For 2020, this factor was found to be .327 kg CO_2/kWh.[9] Figure 1 describes energy sources by percent in Arizona. We assumed the average carbon intensity of electricity and energy makeup for Arizona was the same for Phoenix.

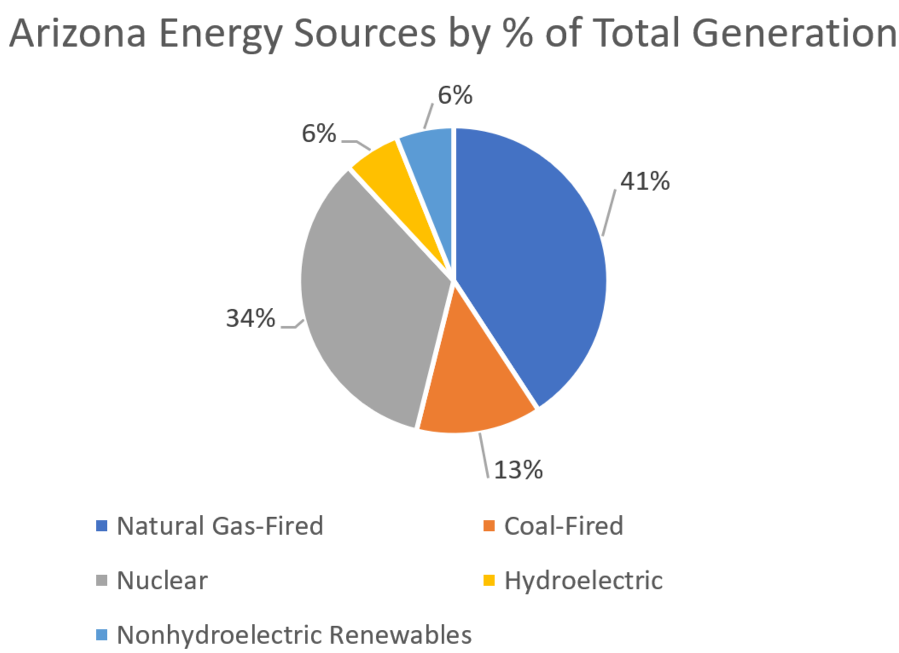

Figure 1: Energy sources in Arizona by percent of total generation for the year 2020.[10] Around 46 percent of power generated in Arizona is from renewable sources or low-carbon sources such as nuclear. As discussed in the Results and seen throughout the Methods, the energy source of the state directly impacts the carbon emissions intensities of electric powered transportation. If the energy sources of a state are dominated by renewables, the carbon intensity for electric transportation will decrease. Petroleum-fired generation was excluded as it contributes less than 0.05% to the energy profile.

Using the annual power consumption, carbon intensity of electricity, and PMT, the CO_2 emissions intensity for the light rail was calculated using the following equation:

$$Carbon\ Intensity\ of\ Light\ Rail\ \left(\frac{kg\ CO2}{pass\ mile}\right) = \frac{Annual\ Electricity\ Use\ (kWh) \times Carbon\ Intensity\ of\ Electricity\ \left(\frac{kg\ CO2}{kWh}\right)}{Annual\ Passenger\ Miles\ (mi)}$$

3.2 Light Rail in Boston

Similar to Phoenix, performance data for the MBTA Light Rail was sourced from the NTD. In 2020, the MBTA reported a light rail efficiency of 0.1 mi/kWh of electricity.[16] In 2019, the MBTA reported 24,400,000 VMT by light rail and 710,000,000 total PMT.[16]

According to the EIA for the state of Massachusetts, 77.5% of electricity in Massachusetts in 2021 came from natural gas-fired power plants.[17] Thus, is it assumed that the electricity used by light rail comes solely from natural gas. The EIA also reported that the average CO_2 emissions per kWh associated with natural gas-fired power plants in 2020 was 0.41 kg/kWh.[18]

For the light rail, the estimated CO_2 emissions intensity in kg/passenger-mile was calculated using the following equation:

$$Carbon\ Intensity\ of\ Light\ Rail\ \left(\frac{kg\ CO2}{pass\ mile}\right) = \frac{Annual\ Vehicle\ Miles\ \times\ Carbon\ Intensity\ of\ Electricity\ \left(\frac{kg\ CO2}{kWh}\right)}{Efficiency\ (mi/kWh)\ \times\ Annual\ Passenger\ Miles\ (mi)}$$

Boston's commuter rail's fuel consumption, VMT, and ridership were sourced from the NTD. The MBTA reported an efficiency of 0.67 mpg of diesel for the commuter rail in 2020.[15] In 2019, 24,900,000 VMT and 653,000,000 PMT were traveled by commuter rail.[16] According to the EPA, in 2021 the CO_2 emissions factor for diesel was 10 kg CO_2/gallon.[19]

For the commuter rail, the estimated CO_2 emissions intensity was calculated using the following equation:

$$Carbon\ Intensity\ of\ Diesel\ Transport\ \left(\frac{kg\ CO2}{pass\ mile}\right) = \frac{Annual\ Vehicle\ Miles\ \times\ Emissions\ Factor\ \left(\frac{kg\ CO2}{gal}\right)}{Fuel\ Efficiency\ (mpg)\ \times\ Annual\ Passenger\ Miles\ (mi)}$$

3.3 Buses in Phoenix

The Valley Metro bus service area extends beyond the boundaries of the city of Phoenix into the broader metro area.[1] It was unclear if performance metrics reported by metro area communities in the NTD were unique values, or double reported. For this analysis, it was assumed that VMT and PMT as reported in the NTD for Phoenix were representative of the Valley Metro. Table 4 shows the operating data for the Valley Metro bus.

	% of Fleet	Annual Passenger Miles	Annual Vehicle Miles Traveled
Bus	100	109,722,464	24,748,005
CNG Bus	73	80,097,399	18,066,044
Diesel Bus	22	24,138,942	5,444,561
Diesel-Hybrid Bus	5	5,486,123	1,237,400

Table 4: 2020 Valley Metro Bus Operating Mileage Data.[5,6,8] In this analysis, the annual passenger miles and annual vehicle miles traveled were distributed to each bus type according to their percentage of the fleet make up. For example, CNG buses account for 73 percent of the fleet and were apportioned 73 percent of annual passenger miles and annual vehicle miles traveled.

Emissions factors for CNG, diesel, and diesel-hybrid buses were used to determine annual emissions for each bus type. The factors consider lifecycle emissions of the fuel, including extraction and refining, and are not limited to vehicle tailpipe emissions.[10] Table 5 describes the CO_2 per mile emissions for each bus type:

Bus Type	Emissions Factor (CO-$_2$ kg/mile)
Diesel	2.680
CNG	2.364
Diesel-Hybrid	2.212

Table 5: CO_2 per mile emissions factors based on bus fuel type.[10]

Lifecycle emissions factors were used because operational efficiency data, such as mile-per-gallon performance, was not available for each bus type.

Using the fleet, operations, and emissions factor, the estimated CO_2 emissions intensity for each bus type were calculated using the following equation:

$$Carbon\ Intensity\ of\ Bus\ Transportation\ (\frac{kg\ CO2}{pass\ mile}) = \frac{Annual\ Vehicle\ Miles\ (mi) \times CO2\ Emissions\ Factor\ (\frac{kg\ CO2}{mi})}{Annual\ Passenger\ Miles\ (mi)}$$

3.4 Buses in Boston

Unlike Phoenix, fuel consumption data, VMT, and ridership of Boston's buses were readily available in the NTD. Thus, a similar process was used to collect data as was used for light rail data collection.

In the NTD, the efficiency of diesel-powered buses was reported as 3.34 mpg in 2020.[15] In 2019, diesel-powered buses traveled 22,300,000 VMT and 257,000,000 total PMT.[16] The efficiency of electric-powered trolley buses was reported as 0.16 mi/kWh in 2020.[15] In 2019, trolley buses traveled 540,000 VMT and 7,100,000 PMT.[16] The efficiency of rapid buses was reported as 1.38 mpg in 2020.[15] In 2019, rapid buses traveled 1,400,000 VMT and 23,200,000 PMT.[16]

The average CO_2 emissions referenced earlier for diesel and electricity from natural gas-fired power plants were used again in this section.

For the commuter rail, buses, and rapid buses (all of which are diesel-powered), the estimated CO_2 emissions intensities were calculated using the following equation:

$$Carbon\ Intensity\ of\ Diesel\ Transport\ (\frac{kg\ CO2}{pass\ mile}) = \frac{Annual\ Vehicle\ Miles\ \times\ Emissions\ Factor\ (\frac{kg\ CO2}{gal})}{Fuel\ Efficiency\ (mpg)\ \times\ Annual\ Passenger\ Miles\ (mi)}$$

For the trolley, the estimated CO_2 emissions intensity was calculated using the following equation:

$$Carbon\ Intensity\ of\ the\ Trolley\ (\frac{kg\ CO2}{pass\ mile}) = \frac{Annual\ Vehicle\ Miles\ \times\ Carbon\ Intensity\ of\ Electricity\ (\frac{kg\ CO2}{kWh})}{Efficiency\ (mi/kWh)\ \times\ Annual\ Passenger\ Miles\ (mi)}$$

3.5 Single Passenger Automobile

As a control, the average carbon intensity of a single passenger automobile was calculated using information from the EPA. In 2021, the fuel efficiency of the average automobile was 25 mpg.[19] On average, 8.8 kg of CO_2 were emitted per gallon of gas used.[23] Thus, we found the average automobile emits 0.352 kg CO_2 per passenger mile.

3.6 Assumptions

Idle times for vehicles were not considered, nor was non-revenue travel in emissions intensity calculations. The analysis was focused on emissions associated with passenger travel, not total emissions of the system.

For the Valley Metro, the fleet makeup was inferred from several publications as a fleet profile was not available. While the actual fleet profile may vary slightly, it was assumed this would not significantly affect overall results. It was also assumed that performance metrics for buses in Phoenix were proportional to the fleet makeup percentage of that bus type (e.g., if diesel buses are 70 percent of the fleet, 70 percent of PMT were attributed to diesel buses). Due to a lack of fleet performance data in Phoenix, emissions factors based on fuel types are assumed to be representative of the average performance of the fleet vehicles.

For the carbon intensity of electricity production, we assumed state averages provided by the EIA were representative of the study areas.

To generate projections for carbon intensity versus factor of increase in ridership, we assumed that carbon intensity would be inversely proportional to an increase in annual PMT by the relationship:

$$Carbon\ Intensity\ \left(\frac{kg\ CO2}{pass\ mile}\right) \propto \frac{1}{Annual\ Passenger\ Miles\ (mi)}$$

4. Results & Discussion

Table 6 shows the results obtained for the carbon intensity of each transportation option provided by the Phoenix Valley Metro.

Transportation Type	Emissions Intensity (kg CO2 / passenger mile)
CNG Bus	0.533
Diesel Bus	0.604
Diesel-Hybrid Bus	0.499

Light Rail	0.085

Table 6: Emissions Intensity of Valley Metro Transportation Operations

Table 7 shows the results obtained for the carbon intensity of each transportation option provided by the MBTA.

Transportation Type	Emissions Intensity (kg CO2 / passenger mile)
Commuter Rail	0.569
Light Rail	0.142
Diesel-Powered Bus	0.260
Rapid Bus	0.437
Trolley Bus	0.196

Table 7: Emissions Intensity of Valley Metro Transportation Operations

Figure 2 shows how the emissions intensities of different public transport modes in Boston and Phoenix differ. The carbon intensity of Phoenix's light rail is lower than Boston's. We believe this may be due to the age of the light rail systems, as the system in Phoenix is only 14 years old while the system in Boston is over 100 years old and is likely more inefficient.[24,25] As expected, the carbon intensity of Boston's trolley bus is lower than that of diesel buses in either Boston or Phoenix since it is powered by electricity.

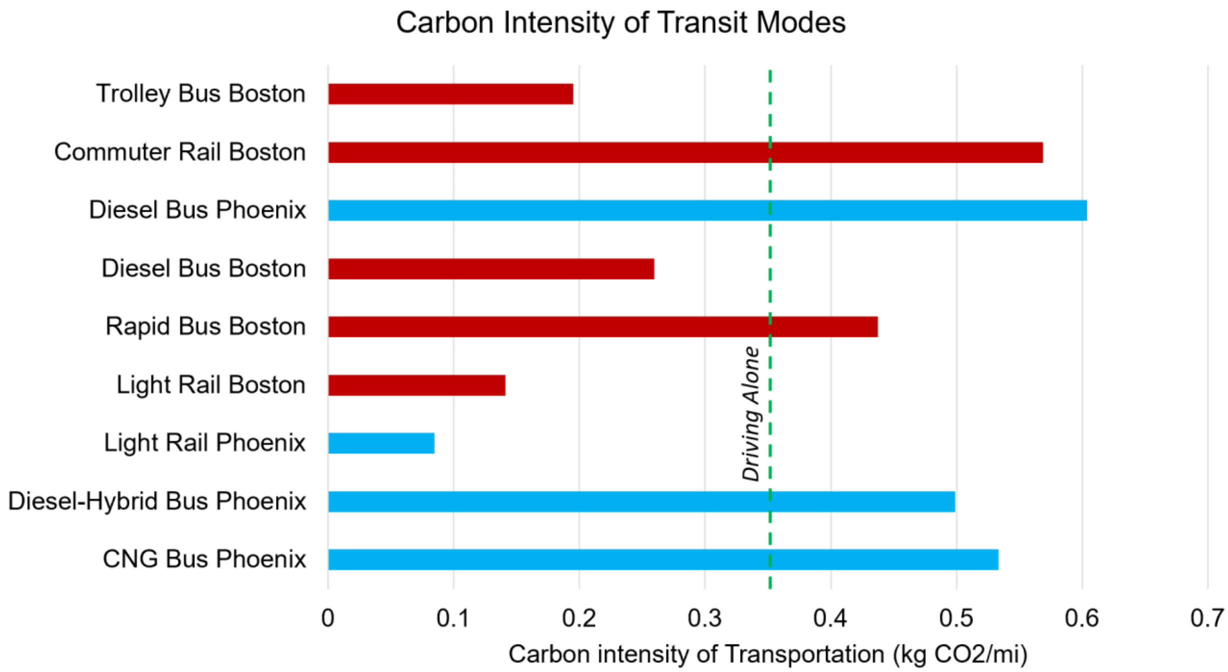

Figure 2: Graph comparing carbon intensity of transit modes for Boston and Phoenix. In Boston, the commuter rail and rapid bus were more carbon intensive than driving alone. All of the buses in Phoenix were also more carbon intensive than driving alone.

We calculated the carbon intensity of Phoenix's diesel-powered buses to be higher than Boston's diesel-powered buses. However, this is not a completely fair comparison as the carbon intensity of Phoenix's buses includes life cycle emissions, while the carbon intensity of Boston's buses includes only operational emissions. We could have calculated the carbon intensity of Boston's buses using the same average life cycle emissions values as Phoenix, but this yielded a lower carbon intensity value of diesel-powered buses in Boston than calculated using VMT, PMT, and ridership. We inferred this means that Boston's buses have higher-than-average carbon emissions, and thus the average life cycle emissions per mile values are not representative of Boston's buses. Finally, we found Boston's commuter rail to have the highest carbon intensity of the transport modes, and to be roughly equivalent to Phoenix's diesel-powered buses.

It is important to note that while some improvements in automobile's carbon intensities can be achieved by carpooling and electrification, the majority of total emissions and local pollutants will still come from automobiles. Whereas if commuters transition from driving cars to riding public transit, there is great potential for carbon intensity to decrease, as is discussed in more detail below. Thus, the results found in this paper do not negate public transportation's potential to decrease transportation's overall carbon emissions.

The differences in carbon intensity for various modes of public transit in Boston and Phoenix suggest different opportunities for system improvement in these cities. For example, light rail and commuter rail modernization could significantly decrease Boston's carbon intensity values, while an electrification of Phoenix's diesel-powered buses significantly decrease Phoenix's carbon intensity values.

In both Boston and Phoenix, increased public transportation ridership would greatly impact current CO_2 emissions per passenger-mile. The MBTA posts information daily on an app about the crowdedness levels of the buses, commuter rails, and light rails.[20] The app has three metrics: not crowded, some crowding, and crowded.[20] Over the last few months, the bus, commuter rail, and light rail were labeled as "not crowded" on over 90% of days, meaning less than 50% of seats were occupied.[20] Thus, we infer the MBTA could double its ridership without needing to expand its infrastructure.

In Phoenix, the light rail operates 20 hours a day[21], with a capacity of 12,000 riders per hour.[22] Average daily ridership for the light rail is 48,000 weekday riders.[22] With a daily capacity of 240,000 riders, the light rail is only utilizing 20% of its daily capacity. While hourly crowdedness metrics were not available for the Phoenix light rail, based on daily ridership, there is ample capacity within the system to expand ridership. Capacity, daily ridership, and crowdedness metrics were not available for the Valley Metro bus system, and thus we were unable to assess the system's ability to handle expanded ridership without needing system expansion.

Figure 3 shows how the carbon intensity per passenger-mile changes as public transit ridership in Phoenix and Boston increases. Carbon intensity exhibits an inverse relationship with the factor of increase in ridership. Thus, if public transit ridership were to double, the carbon emissions per passenger-mile would be cut in half, assuming transportation infrastructure did not need to be expanded. In order for Phoenix's bus system to be less carbon intensive than an automobile, ridership needs to increase by a factor of 1.72 for diesel buses, 1.52 for CNG buses, and 1.43 for light rail. In Boston, ridership needs to increase by a factor of 1.25 for rapid bus and 1.63 for commuter rail.

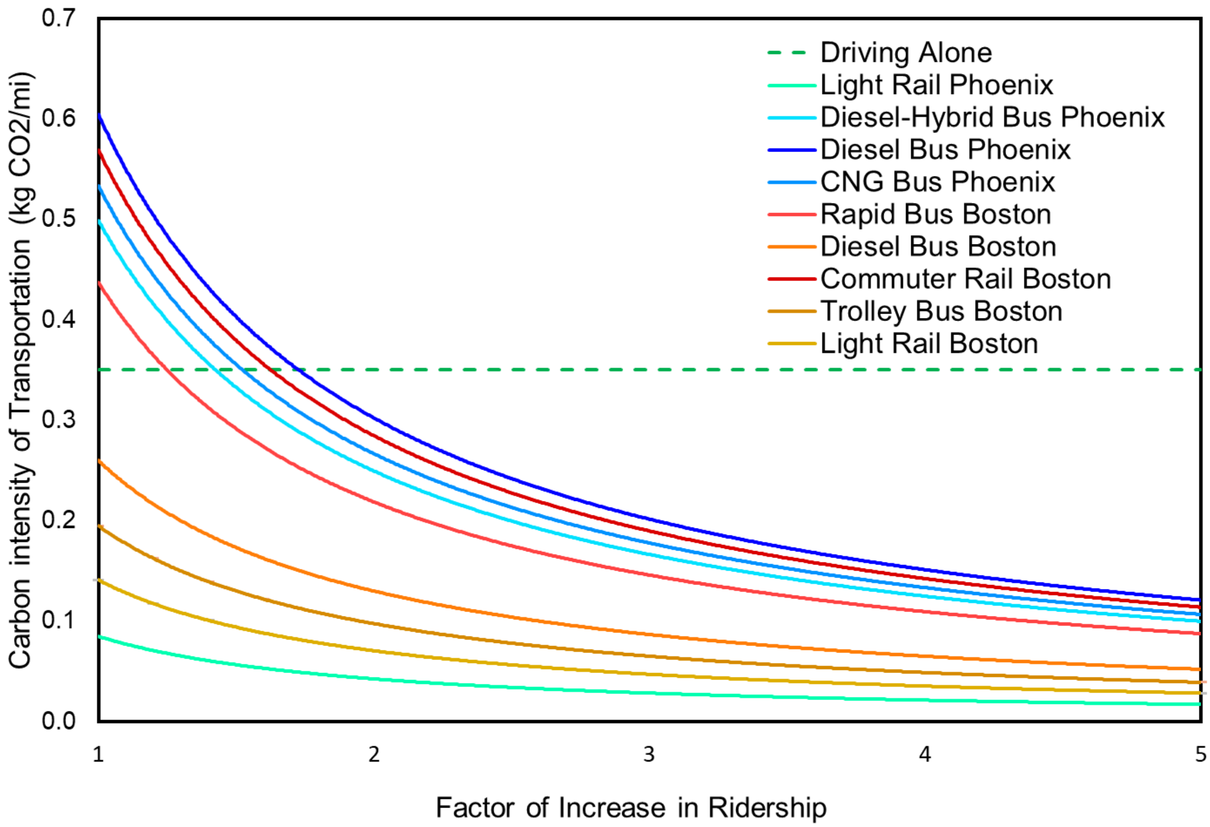

Figure 3: Graph of carbon intensity of transportation v. factor of increase in ridership for modes of transit in Boston and Phoenix. The green line represents the national average carbon intensity of driving a car alone, 0.35 kg CO2/mi.

There remain multiple opportunities for future work. Fleet makeup and performance data were lacking for Phoenix and needed to be inferred in order to complete the analysis. Data availability could be improved by working with transportation authorities to access higher resolution data that includes fuel usage, fuel efficiency, and vehicle miles traveled for each bus and service route. This would allow a more accurate determination of CO_2 emissions per passenger mile and open the door to route optimization based on carbon intensity instead of revenue or travel time. Additionally, this analysis considered only revenue miles. A complete emissions analysis would require fleet operations and performance data which tracked idling times and non-revenue miles.

5. Conclusion

The common metric proposed in this analysis, kg CO_2 emissions per passenger-mile, yielded insights about the performance of the Boston and Phoenix public transportation systems and allowed for a comparative analysis of the systems. Most strikingly, the analysis found that Boston's rapid bus and commuter rail have a carbon intensity about

1.3 and 1.6 times higher, respectively, than an automobile, and all of Phoenix's buses have a carbon intensity between 1.4 and 1.7 times higher than an automobile.

Increasing ridership is an effective measure to improve these systems' carbon intensities. This can be accomplished by optimizing routes, designing city infrastructure to be less car-centric, and lowering or removing fares. In Boston, light rail modernization could improve efficiency and decrease carbon intensity. In general, electrifying public transit systems will decrease carbon intensities as the power grid is decarbonized.

Public transit is an essential service that equitably provides for our communities' mobility needs, and plays an important role in decreasing the carbon emissions of transportation. Our kg CO_2 emissions per passenger-mile metric allows for a comparative analysis of the carbon intensity of a system and suggests improvements for the carbon intensity performance of that system.

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