Texas A&M Transportation Institute

Updated Comparison of Energy Use and Emissions from Different Transportation Modes Using the Latest Available Datasets

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

ABAF	American Bus Association Foundation
AEO	Annual energy outlook
AFDC	Alternative Fuels Data Center
BTS	Bureau of Transportation Statistics
CNG	Compressed natural gas
CO_2	Carbon dioxide
COVID-19	Coronavirus disease 2019
DGE	Diesel gallons equivalent
DOE	Department of Energy
EIA	Energy Information Administration
EPA	Environmental Protection Agency
ERG	Eastern Research Group
EV	Electric vehicle
FHWA	Federal Highway Administration
FTA	Federal Transit Administration
FY	Fiscal year
ID	Identification
IPCC	Intergovernmental Panel on Climate Change
LDSL	Long Distance Service Line
LPG	Liquefied petroleum gas
LTO	Landing and takeoff
MB	Bus
MOVES	MOtor Vehicle Emission Simulator
MY	Model year
NEC	Northeast Corridor
NECSL	Northeast Corridor Intercity Operations Service Line

NEI	National Emissions Inventory
NHTS	National Household Travel Survey
NO_x	Nitrogen oxides
NTD	National Transit Database
NTS	National Transportation Statistics
PM	Particulate matter
PM_{10}	Particulate matter under 10 microns
$PM_{2.5}$	Particulate matter under 2.5 microns
QA/QC	Quality assurance/quality control
RB	Bus rapid transit
RFG	Reformulated gasoline
ROW	Right-of-way
SSSL	State-Supported Service Line
SUT	Source use type
TNC	Transportation network companies
TOS	Type of service
TTI	Texas A&M Transportation Institute
VMT	Vehicle miles traveled
VOMS	Vehicles operated in maximum service

EXECUTIVE SUMMARY

Motorcoaches are passenger-carrying vehicles with a passenger deck located over a baggage compartment that are designed for long-distance travel. This report was developed to evaluate the environmental performance of motorcoach operations by comparing the energy use and amount of pollutants emitted during motorcoach operations to the use and emissions of other transportation modes. This report serves as a continuation of the 2019 *Updated Comparison of Energy Use & Emissions from Different Transportation Modes* report, utilizing the latest available information and emission rates. The results of this study are consistent with the results from the 2019 report—motorcoaches outperformed all other transportation modes in terms of energy efficiency and were among the best performing for all pollutant types modeled.

1 INTRODUCTION

This report describes efforts undertaken in Part 1 of the *Update Modal Energy Use and Emissions and State of U.S. Zero-Emission Coach* project, sponsored by the American Bus Association Foundation (ABAF). The primary task in Part 1 was to update the previous 2019 *Updated Comparison of Energy Use & Emissions from Different Transportation Modes* report [1] (henceforth known as the *2019 report*) with the latest available datasets. Part 2 will examine the state of the zero-emission bus industry for both battery and hydrogen fuel cell electric buses.

1.1 BACKGROUND

The 2019 report evaluated the environmental performance of highway motorcoach operations by comparing their energy use as well as their carbon dioxide (CO_2), nitrogen oxides (NO_x), and particulate matter (PM) emissions to other common transportation modes. As a continuous effort based on the 2014 version of the report, the 2019 report added a comparison with the rideshare mode and applied the latest available government datasets and emission models available at that time.

The results of the 2019 report showed that highway motorcoaches had a relatively low environmental impact compared to other transportation modes on a per passenger-mile basis. For example, highway motorcoaches produced about half the CO_2 emissions of private automobiles and about one-third of the CO_2 emissions of heavy urban rail. Additionally, highway motorcoaches produced very low levels of NO_x and PM emissions. As expected, the 2019 report also found that the environmental performance of highway motorcoaches can be improved further with newer, more fuel-efficient vehicles and by optimizing the routing of motorcoach trips. Overall, the results of the study suggested that highway motorcoaches were a relatively environmentally friendly mode of transportation.

Government datasets, such as the National Transit Database (NTD), the National Transportation Statistics (NTS), and the National Household Travel Survey (NHTS), have been continuously updated on an annual basis since the 2019 report was developed. The electrification of motorcoaches has accelerated over the past several years; this trend is reflected in these datasets. State departments of transportation worked closely with state environmental agencies and federal agencies, led by the U.S. Environmental Protection Agency (EPA), to update the 2020 National Emissions Inventory (NEI) data with the latest available information on air emissions sources of both criteria and hazardous air pollutants.

The U.S. EPA's MOtor Vehicle Emission Simulator (MOVES) is a state-of-the-art model that is used to estimate emissions from mobile sources in the United States. Since publication of the 2019 report, the MOVES has had two major updates—the MOVES3 was released in November 2020, and the MOVES4 was released in August 2023. The transition from the MOVES3 to the MOVES4 included several updates related to vehicle populations, fuel supply, travel activity, and emission rates. The MOVES4 also considered new regulations, improving the accuracy and flexibility of the model for estimating emissions from on-road vehicles. In addition, the MOVES4 included updates that substantially changed how electric vehicles (EVs) were modeled compared to the MOVES3, which affects the activity and emissions of light-duty vehicles [2].

An understanding of trends in motorcoach fueling and key performance indicators can help the ABAF in reviewing the current practices of the motorcoach industry and predicting future developments within the industry across the nation. Thus, the environmental impact of motorcoaches must be updated with the latest available data on energy consumption and emissions and must be based on the latest available emission model, especially given the two major updates to the MOVES since the 2019 report was published.

1.2 Scope of Work

The Texas A&M Transportation Institute (TTI) study team's goal for this report was to provide an updated evaluation of the environmental performance of highway motorcoach operations by comparing the energy use and emissions of motorcoaches with the energy use and emissions of other common transportation modes.

Similar to the 2019 report, the transportation modes considered in this study were motorcoaches,[1] passenger cars,[2] heavy urban rail, light rail, commuter rail, intercity rail (Amtrak), domestic aircraft, urban transit bus, electric trolley bus, ferry boat, vanpool,[3] demand response,[4] and transportation network companies (TNCs). A more detailed

[1] For this study, the motorcoach mode included motorcoach buses used for private charters, tours/sightseeing, scheduled intercity service, and airport and commuter service between a central city and adjacent suburbs/airports.

[2] For this study, passenger cars included all personally owned cars or light trucks used for commuting and other travel.

[3] For this study, only vanpools operated by public entities are included.

[4] For this study, the demand response mode does not encompass private taxis or private shared-ride van services.

description of each transportation mode is available in Appendix A. The pollutant emissions modeled were CO_2 and NO_x, as well as PM under 10 microns (PM_{10}) and PM under 2.5 microns ($PM_{2.5}$).

The TTI team performed the following activities to accomplish this task:

- Conducted a thorough literature review of previous efforts and gathered available data sources for the update of energy use and emissions for all transportation modes.
- Finalized methodologies for calculating energy and emissions based on the availability of data.
- Conducted quality assurance/quality control (QA/QC) and summarized the results.
- Prepared a technical report documenting the activities performed and the results from all previous tasks.
- Prepared a presentation with informational visuals to disseminate the findings.

1.3 Report Chapter Breakdown

This report contains the following chapters:

1. Introduction—This chapter describes the background of this study as well as its scope of work, including goals and objectives.
2. Fuels and Passenger-Miles—This chapter describes the updated fuel consumption and passenger-miles activity for each transportation mode based on the latest available government data.
3. Emission Rates by Fuel Type—This chapter describes the updated CO_2, NO_x, $PM_{2.5}$, and PM_{10} emission rates. These updated rates were retrieved from either the latest available literature (CO_2) or the latest emission models such as the MOVES4.
4. Results—This chapter presents the results of this study.
5. QA/QC—This chapter describes the QA/QC work that the TTI team performed to ensure the input and results were accurate.
6. Summary of Findings—This chapter summarizes the key findings from this study.

2 FUELS AND PASSENGER-MILES

This chapter describes the updated fuel consumption and miles traveled information from the latest available datasets. Because transportation modes with larger capacities naturally consume more energy to operate, it is important to compare the fuel consumption of transportation modes not only by the distance they have traveled but also by the number of passengers included on those trips when estimating benefits.

In this report, fuel consumption is predominantly presented as diesel gallons equivalent (DGE). The DGE serves as a standardized unit employed to compare the energy content among different fuel types. Specifically, the DGE quantifies the amount of fuel with the equivalent energy content of one gallon of diesel. For instance, one gallon of diesel has the same energy content as 1.11 gallons of conventional gasoline; thus, the DGE for conventional gasoline is 1.11 [3]. The measure of vehicle miles traveled in this report is presented in passenger-miles, representing the cumulative sum of the distances traveled by each passenger. For example, 2 passengers riding in a vehicle for 2 miles equals 4 passenger-miles.

The fuel properties used in this study are shown in Table 1. For energy content, the Bureau of Transportation Statistics' (BTS') Energy Consumption by Mode of Transportation dataset was the primary source; when the fuel type information was not available, the Alternative Fuels Data Center's (AFDC's) Fuel Property Comparison data was used instead. Because the density and carbon weight-percentage of the fuels were less likely to change, the TTI team used these values from the 2019 report.

Table 1. Fuel Properties Used

Fuel	Energy Content (Btu/gal)[1,2]	DGE	Density (lb/gal)	Weight Percent Carbon (%)	CO_2 (g/gal)
Diesel	138,700	1.000	7.1	87	10,274
Gasoline	125,000	1.110	6	85	8,482
Liquefied petroleum gas (LPG)	91,420	1.517	4.4	82	6,001
Liquefied natural gas	75,923	1.827	3.2	75	3,992
Compressed natural gas (CNG) in terms of DGE	138,700	1.000	6	75	7,484
Kerosene	135,000	1.027	6.9	86	9,869
B20 biodiesel	126,700	1.095	7	84	9,780

[1]BTS (2023). Energy Consumption by Mode of Transportation. Available at: https://www.bts.gov/content/energy-consumption-mode-transportation

[2]AFDC. Fuel Properties Comparison. Available at: https://afdc.energy.gov/fuels/properties

In the 2019 report, CO_2 emissions per gallon rates were used to calculate CO_2 emissions for the transportation modes. While CO_2 emission rates can be extracted from the MOVES4, the TTI team decided to remain consistent with the methodologies presented in the 2019 report for an apples-to-apples comparison. Thus, using the same equation as the 2019 report for all liquid and gaseous fuels, CO_2 emissions per gallon of fuel burned were calculated using the following equation:

$$\mathrm{CO_2\ (g/gal)} = \mathrm{MW_{CO_2}} \div \mathrm{MW_C} \times 453.6\ \mathrm{g/lb} \times \mathrm{Fuel\ Density\ (lb/gal)} \times \mathrm{Fuel\ Wt\ \%\ Carbon}$$

where $\mathrm{MW_{CO_2}}$ is the molecular weight of CO_2 (44 g/mole); $\mathrm{MW_C}$ is the molecular weight of carbon (12 g/mole), and $\mathrm{Fuel\ Wt\ \%\ Carbon}$ is the carbon weight percentage of the fuel.

2.1 National Transit Database

For the commuter rail, demand response, electric trolley bus, ferry boat, heavy rail, light rail, urban transit bus, and vanpool modes, all energy use and operating data used in the study were taken from the 2021 NTD Annual Database Service and Fuel and Energy [4] datasets, which were the most recent datasets available when this study was conducted. The Annual Database Service database lists financial and operating data from virtually all transit agencies that receive federal operating and capital assistance.

The following fields from the 2021 Fuel and Energy dataset were used [4]:

- NTD identification (ID).
- Mode (vehicle type abbreviation, see Appendix A for definitions).
- Mode vehicles operated in maximum service (VOMS).[5]
- Type of service (TOS).
- Sources of energy (diesel, gasoline, LPG, CNG, biodiesel, electric propulsion, electric battery, and other fuel).

The following fields from the 2021 Annual Database Service dataset were used:

- NTD ID.

[5] In the NTD database, the VOMS is the number of revenue vehicles operated to meet the annual maximum service requirement.

- Mode.
- TOS.
- Time period.
- Passenger-miles.

Table 2 shows the number of separate agencies and vehicles in the analyzed dataset.

Table 2. Data Used for Transit Modes

Transportation Mode	Mode ID	Number of Agencies[1]	Number of Vehicles[1]	DGE	Passenger-Miles[2]	Average Passenger-Miles per DGE	Average Passengers on Board[3]
Commuter Rail	CR	9	3,746	81,662,141	3,011,934,483	36.88	13
Demand Response	DR	216	5,380	18,853,587	115,413,818	6.12	0.9
Ferry Boat	FB	16	84	32,020,026	236,257,443	7.38	69.1
Heavy Rail	HR	14	9,448	83,421,718	7,401,402,604	88.72	11.9
Intercity Rail (Amtrak)		1	284[4]				9.6 (hybrid rail)
Light Rail	LR	21	1,294	18,775,349	890,312,966	47.42	9.6
Transit Bus (Bus [MB]+Bus Rapid Transit [RB])	MB+RB	301	34,399	362,236,585	6,799,694,379	18.77	6.7 (MB: 5, RB: 8.4)
Trolley Bus	TB	5	366	1,189,555	56,164,338	47.21	6.4
Vanpool	VP	30	3,895	2,291,373	223,083,935	97.36	4.7

[1]FTA's 2021 Fuel and Energy dataset [4].
[2]FTA's 2021 NTD Annual Database Service. Available at: https://www.transit.dot.gov/ntd/data-product/2021-annual-database-service
[3]FTA's 2021 NTD: National Transit Summaries & Trends, Exhibit 37: 2021 Average Passengers on Board [5].
[4]Amtrak's Equipment Appendices. Available at: https://www.amtrak.com/content/dam/projects/dotcom/english/public/documents/corporate/businessplanning/Amtrak-Equipment-ALP-Appendices-FY22-27.pdf

The values shown in Table 2 were derived using the following procedures:

1. The passenger-miles information for the Annual Total time period was merged into the Fuel and Energy dataset [4] using the NTD ID, Mode, and TOS.
2. The TOS was filtered by Directly Operated.
3. For each Mode, the count of NTD IDs associated with a Mode was calculated. These values represented the number of agencies.

4. For each Mode, the sum of Mode VOMS associated with a Mode was calculated. These values represented the number of vehicles in the Mode. For intercity rail, the values were retrieved from Amtrak.

5. For each NIS ID and Mode, the Source of Energy for each mode was summed as follows:

    - For gasoline, LPG, CNG, and biodiesel, the following equation and the energy content (in British thermal units per gallon) in Table 1 were used to convert the sum of fuel (in gallons) by Mode to DGEs:

    $$DGE = Energy\ (gal)\ x\ Fuel\ Energy\ Content\ (Btu/gal) \div Diesel\ Energy\ Content\ (Btu/gal)$$

    - For electric propulsion and electric battery, the sum of energy (in kilowatt-hours) was converted to DGEs using the following equation:

    $$DGE = Energy\ (kWh)\ x\ 3{,}412\ Btu/kWh \div Diesel\ Energy\ Content\ (Btu/gal)$$

    - For other fuels, the energy was reported as a gallon per gallon equivalent and was converted to DGEs using the following equation:

    $$DGE = Energy\ (gal/gal\ equivalent) \div Diesel\ Energy\ Content\ (Btu/gal)$$

    - Then, the DGEs for each mode were summed. These values represented the number of DGEs.

6. For each Mode, the passenger-miles were summed. These values represented the number of passenger-miles.

2.2 Aircraft Data

According to the BTS, domestic U.S airlines in 2021 used 9,938 million gallons of jet fuel (kerosene) and had an average aircraft-mile flown per gallon of 0.57 mpg [6]. The 2021 passenger-miles for U.S. air carriers were 573,404 million miles [7]. Thus, the TTI team calculated the passenger-miles per gallon of kerosene used as 57.7 mpg or
59.2 passenger-miles/DGE.

2.3 AMTRAK DATA

To evaluate the difference between Amtrak's Northeast Corridor (NEC) operations and operations in all other Amtrak corridors for fiscal year (FY) 2021, passenger-miles for each type of operation—the Northeast Corridor Intercity Operations Service Line (NECSL), State-Supported Service Line (SSSL), and Long Distance Service Line (LDSL)—were retrieved from Amtrak's *Five-Year Plans: Service and Asset Line Plans (FY 2022–2027)* [8]. For FY 2021, the actual passenger-miles for the NECSL, SSSL, and LDSL were 754.1 million, 809.6 million, and 1,294.9 million miles, respectively. The NEC operations accounted for 26.4 percent of all operations in FY 2020, which was slightly lower than the 30 percent in FY 2017 reported in the 2019 report [1] and the 29.4 percent in FY 2020 that the TTI team calculated from Amtrak's *Five-Year Plans: Service and Asset Line Plans (FY 2021–2026)* [9]. According to Table 4 in Amtrak's FY 2022 five-year plans [8], electric traction was only available on the NEC main and branch lines. Thus, like the 2019 report, this study assumed that all electricity used by Amtrak in FY 2021 was for NEC operations, and all diesel fuel used was for operations in other corridors. Under this assumption, the passenger-miles for electricity were calculated to be **754.1 million miles**, whereas the passenger-miles for diesel were calculated to be **2,104.5 million miles**.

Based on Amtrak's *FY 2022 Sustainability Report* [10], Amtrak's diesel fuel use was 40.2 million gallons in FY 2021. However, because propulsion electric use was not reported by any of the Amtrak FY 2021 reports, the TTI team instead utilized the values acquired from the BTS's Amtrak Fuel Consumption and Travel data[6], which reported Amtrak's fuel consumption to be **44 million gallons of diesel** and **388 million kWh of electricity** for calendar year 2021. The discrepancy between the Amtrak report and the BTS data may result from the difference in fiscal and calendar years. Thus, using the BTS data, the TTI team calculated the passenger-miles per DGE to be **47.8 passenger-miles/DGE** for diesel and **79 passenger-miles/DGE** for electric.

The BTS's Amtrak Fuel Consumption and Travel data also showed that the Amtrak locomotives traveled 28 million miles in 2021. Assuming a uniform diesel-electric distribution and the fuel consumption values listed above, the TTI team calculated the Amtrak locomotives to have an average fuel efficiency of 0.47 mpg for the diesel-powered fleet and 0.02 miles/kWh for the electric fleet (or 0.77 miles/DGE).

[6]BTS Amtrak Fuel Consumption and Travel data. Available at: https://www.bts.gov/content/amtrak-fuel-consumption-and-travel-1

2.4 Motorcoach Industry Data

Table 3 shows the motorcoach data used in this study, which showcased the 2015, 2017, 2019, and 2020 survey years. Data on motorcoach miles operated and fuel consumed were taken from both the 2017 [11] and 2020 [12] *Motorcoach Census* reports. Fuel consumption information from the 2017 *Motorcoach Census* was utilized because the 2020 *Motorcoach Census* did not report on fuel consumption. The 2020 *Motorcoach Census* noted that the values were significantly lower in 2020 than in 2019 due to the effects of the Coronavirus disease 2019 (COVID-19) pandemic.

Table 3. Motorcoach Data Used

Survey Year	Service Type	Service Mileage	Service Fuel Consumption (gal)	Miles per Gallon	Average Passenger Load	Service Passenger-Miles	Service Passenger-Miles per Gallon
2015	Charter, Tour, Sightseeing	1,099,735,672	209,482,448	5.25	37	38,530,711,392	183.93
2015	Fixed-Route	864,078,028	164,593,352	5.25	36	31,106,809,008	188.99
2015[a]	Total	1,963,813,700	374,075,800	5.25	35.46	69,637,520,400	186.16
2017	Charter, Tour, Sightseeing	824,395,600	128,548,056	6.41	33.7	35,150,666,900	273.44
2017	Fixed-Route	647,739,400	101,002,044	6.41	45	29,148,273,000	288.59
2017[a]	Total	1,472,135,000	229,550,100	6.41	43.68	64,298,939,900	280.11
2019	Charter, Tour, Sightseeing	991,364,360	**177,627,418**[c]	**5.58**[c]	36.3	33,898,240,960	**190.84**[c]
2019	Fixed-Route	778,929,140	**139,564,400**[c]	**5.58**[c]	36	28,041,449,040	**200.92**[c]
2019[b]	Total	1,770,293,500	**317,191,818**[c]	**5.58**[c]	34.99	61,939,690,000	**195.28**[c]
2020	Charter, Tour, Sightseeing	379,244,096	NA	NA	29.6	12,096,021,004	NA
2020	Fixed-Route	297,977,504	NA	NA	24	7,151,460,096	NA
2020[b]	Total	677,221,600	NA	NA	28.42	19,247,481,100	NA

[a]2017 *Motorcoach Census* [11].
[b]2020 *Motorcoach Census* [12].
[c]Values in **bold** were calculated by the TTI team.

Fuel consumption was not reported in the 2020 *Motorcoach Census*, so the TTI team estimated it by interpolating between the 2015 and 2017 values. However, the 2020 service mileage was an outlier and was significantly lower than either value. Interpolation with the 2020 service mileage produced an unrealistic fuel consumption value. Thus, the TTI team decided to use the values from 2019 (the next latest available) instead because they fell between the 2015 and 2017 values. The TTI team's interpolated 2019 fuel consumption values and calculated miles per gallon values were **317,191,818 gallons of fuel consumed** and **5.58 mpg**, respectively.

The average passenger loads for charter, packaged tour, sightseeing, and fixed-route services were listed in the surveys. Similar to the 2019 report [1], the TTI team averaged the charter, tour, and sightseeing passenger loads into a single value. Because the breakdown between the fixed-route and the charter/tour/sightseeing group was not provided in either survey, the TTI team elected to use a 43.7/56.3 fixed-route to charter/tour/sightseeing ratio that was employed in both the 2014 and 2019 reports by the ABAF to determine how to allocate the total service mileage among these groups. The TTI team then assumed the average miles per gallon to be equal across all service types and calculated the service fuel consumption (the service mileage divided by the miles per gallon) and service passenger-miles (the service mileage multiplied by the average passenger load; for the charter/tour/sightseeing group, it was the difference between fixed-route and the total).

Note that the information shown in this section represents all motorcoaches from both the United States and Canada. The majority (27,753 or 90 percent) of the motorcoaches in the 2020 *Motorcoach Census* were from the United States.

2.5 Passenger Car Data

The TTI team retrieved fuel efficiency information [13] from the NTS website. In calendar year 2021, the average fuel efficiency for short- and long-wheelbase vehicles[7] was 25 mpg and 17.8 mpg, respectively. The average U.S. light-duty vehicle fuel efficiency in calendar year 2021 was **22.8 mpg of gasoline or 25.3 miles/DGE**.

To evaluate the range of potential energy use per passenger-mile from different vehicles, the TTI team evaluated the fuel efficiency of the 2021 Toyota Prius Eco and Jeep Cherokee 4WD models, which represented a hybrid and a sports utility vehicle, respectively. Similar to the 2019 report [1], the TTI team treated the Prius' fuel efficiency as the minimum fuel use per passenger-mile for private passenger cars, whereas the Cherokee's fuel efficiency was treated as the maximum. The fuel efficiency information was retrieved from the U.S. Department of Energy's (DOE's) Fuel Economy website [14].

[7]Short-wheelbase vehicles include passenger cars, light trucks, vans, and sport utility vehicles with wheelbases equal to or less than 121 inches. Long-wheelbase vehicles include large passenger cars, vans, pickup trucks, and sport utility vehicles with wheelbases more than 121 inches.

The Prius had a combined city/highway fuel efficiency of **56 mpg of gasoline or 62.1 miles/DGE**, while the Cherokee had a combined city/highway fuel efficiency of **22 mpg of gasoline or 24.4 miles/DGE**.

2.6 Transportation Network Company Data

TNCs are a major part of the demand response mode; however, the Federal Transit Administration (FTA) removed TNC data from the NTD because only eight agencies nationwide reported this type of service in FY 2021 [5]. Thus, the demand response category in Table 2 does not contain information on TNCs.

In the 2019 report [1], data on average passengers per trip and average loaded and unloaded trip lengths for TNCs were taken from Schaller Consulting's *The New Automobility: Lyft, Uber and the Future of American Cities* [15] and from the 2017 NHTS. However, the largest TNCs (Uber, Lyft, and DiDi) reported losses in 2018 through 2020. In addition, several state and federal laws have been enacted since 2019 that reclassify TNC contractors as employees (e.g., Assembly Bill 5 and Proposition 22 in California). Thus, the TTI team suspected that the values from the 2018 Schaller Consulting report [15] and the 2017 NHTS (the latest available update) were no longer representative of the TNC information in 2021.

The TTI team was able to acquire more recent TNC information from the Federal Highway Administration's (FHWA's) *Analysis of Travel Choices and Scenarios for Sharing Rides* [16], which was published in 2021. As stated in this FHWA report, TNC nonpassenger-miles accounted for 42 percent of the total vehicle miles. With passengers, the average occupancy rate was 1.475 and the average trip length was 5.6 miles. Based on the TNC nonpassenger-miles percentage, the TTI team calculated the average unloaded mileage between passenger trips to be 4.1 miles. In the 2019 report for comparison, the average occupancy rate was 1.5, the average passenger trip length was 5.2 miles, and the average unloaded mileage between passenger trips was 3 miles.

Finally, the TTI team calculated the average passenger-miles per vehicle-miles driven (the average trip length with passengers multiplied by the average occupancy rate divided by the total trip length) to be **0.85 passenger-miles/vehicle-miles driven** (compared to 0.95 in the 2019 report).

3 EMISSION RATES BY FUEL TYPE

This section discusses the NO_X and PM emission rates (in grams per mile) used in this study. As mentioned in the previous chapter, CO_2 emission rates were calculated using a formula (refer to Table 1) rather than retrieved through the outputs of an emission model. For on-road vehicles (i.e., private autos, vanpool vehicles, demand response vehicles, transit buses, and coach buses), the NO_X and PM emission rates were obtained from the U.S. EPA's latest MOVES4. For nonroad modes, the TTI team conducted an extensive literature review of government reports and datasets to either update or replace the NO_X and PM emission rates from the 2019 report; several data sources referred to in the 2019 report were decades old. The rationale behind choosing the new data sources is documented in this chapter.

3.1 On-Road Vehicles

The NO_X and PM emission rates for all on-road vehicles were derived using the U.S. EPA's MOVES4.

3.1.1 MOVES4 Scale

For this study, the MOVES4 was executed for the On-Road model, the Default Scale domain, and the Inventory calculation type.

3.1.2 MOVES4 Time Span

Because the latest updated data for a majority of the sources were for the year 2021, the time span selected for this study was the year 2021. All hours of the day were selected; however, to reduce the computational load and processing time, the TTI team opted to only model the month of July and weekdays.

3.1.3 MOVES4 Geographical Bounds

Again, to reduce the computational load and processing time, the TTI team opted to only model Dallas County, Texas (Federal Information Processing Standards Code 48113). Dallas County is home to over 2.5 million residents and houses several major roadways with the highest annual average daily traffic in the region. Note, however, that the MOVES4 has incorporated the effects of the soon-to-be-required reformulated gasoline (RFG) for Dallas County, which may lower NOx emission rates [2]. For due diligence, the TTI team compared the MOVES4 Dallas County NOx emissions for model year 2021 to the NOx emissions for Harris County, Texas, and confirmed that the difference was minimal. Thus, the TTI team believed that by using Dallas County as a surrogate, the MOVES4 was unlikely to produce emission rates below the national average (i.e., to underestimate the emission rates).

3.1.4 MOVES4 On-Road Vehicle Types

For the on-road vehicle selection, the following Source Use Types (SUTs) were modeled: private autos—Passenger Cars, vanpool vehicles—Passenger Trucks, transit buses—Transit Buses, motorcoaches—Other Buses,[8] and demand response vehicles—Light Commercial Trucks.

3.1.5 MOVES4 Road Types

All five road types defined in the MOVES4—Off-Network, Rural Restricted Access, Urban Restricted Access, Rural Unrestricted Access, and Urban Unrestricted Access—were selected.

3.1.6 MOVES4 Pollutants and Processes

The following pollutants were selected in the MOVES4 for analysis: Atmospheric CO_2, NO_x, Primary Exhaust $PM_{2.5}$—Total, Primary Exhaust $PM_{2.5}$—Brakewear Particulates, Primary Exhaust $PM_{2.5}$—Tirewear Particulates, Primary Exhaust PM_{10}—Total, Primary Exhaust PM_{10}—Brakewear Particulates, and Primary Exhaust PM_{10}—Tirewear Particulates.

The processes included were Running Exhaust (processID=1), Start Exhaust (processID=2), Brakewear (processID=9), Tirewear (processID=10), Crankcase Running Exhaust (processID=15), and Crankcase Start Exhaust (processID=16).

3.1.7 MOVES4 Emissions Output Detail

For output aggregation, the time was set to Hour and the geographic area was set to County. All boxes were checked in the All Vehicle/Equipment Categories and On-Road sections in the Output Emissions Detail tab. No boxes were checked in the Nonroad section.

[8] In the 2019 report [1], the MOVES2014b used the term Intercity Buses for this category. This term was changed to Other Buses with the release of the MOVES3 and the subsequent MOVES4.

3.1.8 MOVES4 Rates Per Distance Output

Table 4 shows the MOVES4 rates per distance output. For the model year (MY) 2021 fleet age, the emission rates for each transportation mode and fuel type were calculated only for modelYearID=2021. For the 2021 Fleet Average, the emission rate was calculated for the entire fleet, which ranged from MY 1991 to MY 2021. The total emission quantity from the MOVES4 output table was summed for each pollutant, SUT, fuel type, and MY. Then, the emission quantity was divided by the sum of activity from the MOVES4 activity output table, which in this case was the distance traveled (activityID=1) for each SUT, fuel type, and MY. The fleet average value was calculated by first summing the emission quantities for all processes listed in Section 3.1.6 and the distances traveled for all MYs and then dividing the total emission quantity by the total distance traveled.

Table 4. MOVES4 Emission Rates per Distance Output

Transportation Mode	Fleet Age	Fuel Type	Percent Energy Content (%)	NO_X (g/mile)	PM_{10}[1] (g/mile)	$PM_{2.5}$[1] (g/mile)
Passenger Car	MY 2021	Gasoline	100	0.022	0.0333	0.0054
Passenger Car	2021 Fleet Average	Gasoline	100	0.184	0.0356	0.0075
Vanpool	MY 2021	Gasoline	100	0.023	0.0357	0.0059
Vanpool	2021 Fleet Average	Gasoline	100	0.281	0.0390	0.0087
Transit Bus	MY 2021	Diesel	100	1.830	0.1130	0.0172
Transit Bus	2021 Fleet Average	Diesel	100	3.078	0.1419	0.0458
Motorcoach	MY 2021	Diesel	100	2.315	0.2049	0.0295
Motorcoach	2021 Fleet Average	Diesel	100	6.233	0.4097	0.2295
Demand Response[2]	MY 2021	Gasoline	71	0.026	0.0363	0.0063
Demand Response[2]	MY 2021	Diesel	29	0.258	0.0398	0.0093
Demand Response[2]	2021 Fleet Average	Gasoline	71	0.444	0.0423	0.0068
Demand Response[2]	2021 Fleet Average	Diesel	29	2.135	0.1144	0.0737

[1]Total of exhaust, brakewear, and tirewear pollutants.

[2]For the demand response mode, gasoline or natural gas vehicles accounted for about 71 percent of the vehicle miles traveled (VMT), whereas diesel or other fuel vehicles accounted for about 29 percent of the VMT [4].

3.2 Nonroad Vehicles

Similar to the 2019 report, the emission rates for nonroad vehicles were obtained by reviewing data and documentation instead of modeling emissions.

3.2.1 Aircraft

The 2019 report utilized the NO_x emissions per landing and takeoff (LTO) (10.2 kg/LTO) from the Intergovernmental Panel on Climate Change's (IPCC's) *Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories—Aircraft Emissions* [17] published in 2000 and the air taxi PM_{10} emissions per LTO (0.60333 lb/LTO) from the U.S. EPA's *Documentation for Aircraft, Commercial Marine Vessel, Locomotive, and Other Nonroad Components of the National Emissions Inventory, Volume 1—Methodology* [18] published in 2005.

The TTI team reviewed the emission rates used by the Eastern Research Group (ERG) to develop the aviation component in the 2020 NEI [19]. Table 5 shows the emission rates for NO_x, PM_{10}, and $PM_{2.5}$ along with the number of LTOs for each aircraft type in 2020. The weighted average was based on the number of LTOs per aircraft type. Using the same conversion rates as the 2019 report (1,874 lb of fuel/LTO and 6.8 lb/gal), the TTI team calculated the NO_x, PM_{10}, and $PM_{2.5}$ emission rates as **6.16 g/gal, 0.72 g/gal, and 0.64 g/gal**, respectively.

Table 5. Number of LTOs in 2020 and Aircraft Emissions per LTO

Aircraft Type	Number of LTOs in 2020	NO_x (lb/LTO)	NO_x (g/LTO)	PM_{10} Primary (lb/LTO)	PM_{10} Primary (g/LTO)	$PM_{2.5}$ Primary (lb/LTO)	$PM_{2.5}$ Primary (g/LTO)
Commercial	5,304,089	18.58	8,427.74	1.08	489.88	1.05	476.27
Air Taxi (Turbine)	3,233,536	0.78	353.80	0.60	272.16	0.59	267.62
Air Taxi (Piston)	490,315	0.16	72.57	0.60	272.16	0.42	190.51
General Aviation (Turbine)	15,671,335	0.32	145.15	0.24	108.86	0.23	104.33
General Aviation (Piston)	22,432,799	0.07	31.75	0.24	108.86	0.16	72.57
Military	3,693,002	22.33	10,128.71	1.39	630.49	1.36	616.89
Weighted Average		**3.74**	**1,697.46**	**0.44**	**198.49**	**0.39**	**177.59**

3.2.2 Commuter Rail and Intercity Rail (Amtrak)

The TTI team was able to update the emission rates for commuter rail (Table 6) and intercity rail (Amtrak) (Table 7) based on information from ERG's *2020 NEI Locomotive Methodology* [20].

Table 6. 2020 Fleet Emission Rates for Commuter Rail

Agency	NO_x (g/gal)	PM_{10} (g/gal)	$PM_{2.5}$ (g/gal)
Association of American Railroads	120.48	3.04	2.95
Metra (Illinois)	152.74	4.76	4.62
Massachusetts Bay Transportation Authority	137.13	3.49	3.39
Average	**136.78**	**3.76**	**3.65**

Source: ERG's *2020 NEI Locomotive Methodology* [20].

Table 7. 2020 Fleet Emission Rates for Intercity Rail (Amtrak)

Agency	NO_x (g/gal)	PM_{10} (g/gal)	$PM_{2.5}$ (g/gal)
Amtrak	155.21	5.23	5.07

Source: ERG's *2020 NEI Locomotive Methodology* [20].

The 2020 NO_x emission rate for Amtrak's intercity rail was comparable to the value in the 2019 report; however, its PM emission rates were slightly higher (5.23 g/gal for PM_{10} and 5.07 g/gal for $PM_{2.5}$ versus 4.2 g/gal for PM). Regarding commuter rail, the Metra (Illinois) emission rates most closely tracked the 2019 report values; however, the TTI team believed using an average value for the three datasets would be most appropriate.

Using the passenger-miles and fuel consumption values listed in Section 2.3, the TTI team calculated the passenger-miles per DGE for the diesel and electric Amtrak railways as 47.8 and 0.05 passenger-miles/DGE, respectively. Because the percentage of diesel and electric railways are 73.6 percent and 26.4 percent, respectively, the weighted average for Amtrak's intercity rail was **35.2 passenger-miles/DGE**.

3.2.3 Electric Modes

For electric modes (i.e., electric commuter rail, electric intercity rail, heavy rail, light rail, and trolley buses), NO_x and PM emissions per kilowatt-hour of electricity used were calculated based on the U.S. average emission rates for electric utilities in 2021.

Based on information contained in the Energy Information Administration's (EIA's) 2021 Annual Energy Outlook *(*AEO), the net generation of electricity in 2021 was 4,108,303 thousand-MWh [21], whereas the NO_x emissions from conventional power plants and combined-heat-and-power plants in 2021 were 1,253 thousand metric tons [22]. This emissions data included total emissions from both the generation of electricity and the production of useful thermal output. The average NO_x emission rate for electricity generation was **0.3 g/kWh**, slightly higher than the 0.235 g/kWh reported in the 2019 report.

The PM emission rates were calculated by dividing the total electric utility PM available from the 2020 NEI by the total electric utility generation in 2020 available from the EIA's AEO (4,009,767 thousand-MWh) [21]. The total electric utility emissions for PM_{10} and $PM_{2.5}$ were 100,672.21 and 85,458.95 tons, respectively.[9] Thus, the TTI team calculated the PM emission rates to be **0.025 g/kWh for PM_{10} and 0.021 g/kWh for $PM_{2.5}$**.

3.2.4 Ferry Boats

In the 2019 report, ferry boat emission rates were retrieved from the U.S. EPA's 2005 methodologies report [18]. Because this source is nearly 20 years old, the TTI team decided to replace it with the ferry boat (harbor craft) emission rates from the U.S. EPA's 2022 *Port Emissions Inventory Guidance* [23]. Specifically, the average emission rates for NO_x, PM_{10}, and $PM_{2.5}$ were obtained from Table H.7. Average Harbor Craft Emission Factors by Engine Tier in this report.

Assuming that the fuel used by these harbor craft engines was diesel, which produces 37.31 kWh per gallon,[10] Table 8 lists the harbor craft emission rates by engine tier. Because older harbor craft engines have substantially higher emissions than newer engines, the TTI team decided to use a weighted average instead of a simple average to determine the fleet emission rates. The TTI team reviewed the latest emission inventories from the largest ports in the United States[11] and acquired the average tier composition of harbor crafts (Tier 0=29 percent, Tier 1=6 percent, Tier 2=26 percent, Tier 3=27 percent, and Tier 4=12 percent) to weight the emission rates.

[9]2020 NEI. Available at: https://www.epa.gov/air-emissions-inventories/2020-nei-supporting-data-and-summaries. PM_{10} and $PM_{2.5}$ Primary were selected as Tier 1 Summaries—Criteria Air Pollutants and Fuel Comb Elec Util was selected as Tier 1 Category.

[10]U.S. DOE's Fuel Conversion Factors to Gasoline Gallon Equivalents webpage. Available at: https://epact.energy.gov/fuel-conversion-factors

[11]Latest emission inventories for Los Angeles (2022), Long Beach (2022), New York-New Jersey (2021), and Houston (2019). Available at: https://kentico.portoflosangeles.org/getmedia/409590b5-0e6a-4c15-8d9b-fcdb02624933/2022_Air_Emissions_Inventory, https://polb.com/download/14/emissions-inventory/17867/2022-air-emissions-inventory.pdf, https://www.panynj.gov/content/dam/port/our-port/air-emissions-inventory-reports/PANYNJ-2021-Multi-Facility-EI-Report.pdf, and https://www.porthouston.com/wp-content/uploads/2022/11/Port-Houston-2019-GMEI-Report_Dec-2021.pdf

Table 8. Harbor Craft Emission Rates by Engine Tier

Tier	NO_x (g/kWh)	PM_{10} (g/kWh)	$PM_{2.5}$ (g/kWh)	NO_x (g/gal)	PM_{10} (g/gal)	$PM_{2.5}$ (g/gal)
Tier 0	10.28	0.26	0.25	383.64	9.66	9.37
Tier 1	9.62	0.26	0.25	359.11	9.66	9.37
Tier 2	5.64	0.15	0.14	210.53	5.52	5.36
Tier 3	4.75	0.08	0.08	177.21	3.10	3.00
Tier 4	1.30	0.03	0.03	48.51	1.12	1.09
Weighted Average	**6.46**	**0.16**	**0.15**	**241.21**	**5.79**	**5.61**

Source: U.S. EPA's *Port Emissions Inventory Guidance: Methodologies for Estimating Port-Related and Goods Movement Mobile Source Emissions* [23].

3.3 Summary

Table 9 summarizes the NO_x and PM emission rates.

Table 9. NO_x and PM Emission Rates

Transportation Mode	Description	Fleet Age	Fuel	Unit	NO_x Emission Rate	PM_{10} Emission Factor	$PM_{2.5}$ Emission Factor
Passenger Car	Passenger Car	MY	Gasoline	g/mile	0.022	0.0333	0.0054
Passenger Car	Passenger Car	Fleet Average	Gasoline	g/mile	0.184	0.0356	0.0075
Vanpool	Passenger Truck	MY	Gasoline	g/mile	0.023	0.0357	0.0059
Vanpool	Passenger Truck	Fleet Average	Gasoline	g/mile	0.281	0.0390	0.0087
Transit Bus	Transit Bus	MY	Diesel	g/mile	1.830	0.1130	0.0172
Transit Bus	Transit Bus	Fleet Average	Diesel	g/mile	3.078	0.1419	0.0458
Motorcoach	Other Buses	MY	Diesel	g/mile	2.315	0.2049	0.0295
Motorcoach	Other Buses	Fleet Average	Diesel	g/mile	6.233	0.4097	0.2295
Demand Response	Light Commercial Truck	MY	Gasoline	g/mile	0.026	0.0363	0.0063
Demand Response	Light Commercial Truck	Fleet Average	Gasoline	g/mile	0.258	0.0398	0.0093
Demand Response	Light Commercial Truck	MY	Diesel	g/mile	0.444	0.0423	0.0068
Demand Response	Light Commercial Truck	Fleet Average	Diesel	g/mile	2.135	0.1144	0.0737
Ferry Boat	Type II Harbor Craft	2022	Diesel	g/gal	241.21	5.79	5.61
Air	Jet Aircraft	2020	Diesel	g/gal	6.16	0.72	0.64
Commuter Rail	Locomotive	2020	Diesel	g/gal	136.78	3.76	3.65
Commuter Rail	Locomotive	2020	Electric	g/kWh	0.3	0.025	0.021
Intercity Rail (Amtrak)	Locomotive	2020	Diesel	g/gal	155.21	5.23	5.07

Transportation Mode	Description	Fleet Age	Fuel	Unit	NO_X Emission Rate	PM_{10} Emission Factor	$PM_{2.5}$ Emission Factor
Intercity Rail (Amtrak)	Locomotive	2020	Electric	g/kWh	0.3	0.025	0.021
Heavy Rail	Electric Propulsion Car	2021	Electric	g/kWh	0.3	0.025	0.021
Light Rail	Electric Propulsion Car	2021	Electric	g/kWh	0.3	0.025	0.021
Trolley Bus	Electric Trolley	2021	Electric	g/kWh	0.3	0.025	0.021

4 RESULTS

This chapter describes the results of the study. Section 4.1 describes the methodology and emission calculations for CO_2. It also discusses the energy consumption by each transportation mode. Section 4.2 describes the methodology and emission calculations for NO_x and PM.

4.1 CO_2 EMISSIONS AND ENERGY CONSUMPTION

4.1.1 Methodology

The total CO_2 emissions for each mode was calculated using the following equation (the fuel properties used were shown in Table 1):

$$\text{Total CO}_2\text{ (g)} = \text{Sum}\left(\text{CO}_2\left(\frac{\text{g}}{\text{gal}}\right)\text{x Annual Gallons}\right)_{\text{AllFuels}} + \text{Electricity (kWh) x 600.6 g}_{\text{CO}_2}/\text{kWh}$$

The CO_2 emissions per passenger-mile were calculated using the following equation:

$$\text{CO}_2\text{ per Passenger Mile }\left(\frac{\text{g}}{\text{pass} - \text{mi}}\right) = \text{Total CO}_2\text{ (g)} \div \text{Annual Passenger Miles}$$

4.1.2 Emissions Calculation

Table 10 shows the average energy use and CO_2 emissions by transportation mode. These results are also visualized in Figure 1 through Figure 3.

Similar to the 2019 report, the high and low figures for motorcoaches are based on average passenger loads for different industry segments (charter/tour/sightseeing versus fixed-route service). For the other public modes, the high and low figures are based on the range of results from individual transit agencies in the NTD database (i.e., the minimum and maximum passenger-miles divided by the sum of fuel in DGE by the NTD ID). For private autos and TNCs, as discussed in Section 2.5, the averages are based on U.S. fleet average fuel economy (25.3 miles/DGE), while the high and low figures are based on the use of a sport utility vehicle (24.4 miles/DGE) and the use of a hybrid car (62.1 mile/DGE), respectively.

As shown below, motorcoaches on average used 710 Btu/passenger-mile (Figure 1) and produced 52.6 g of CO_2/passenger-mile (Figure 3). On average, motorcoaches used the least amount of energy and produced the lowest CO_2 emissions per passenger-mile of any of the transportation modes analyzed.

Table 10. Energy Use and CO_2 Emission (g/Passenger-Mile), by Mode

Transportation Mode	Passenger-Miles per DGE			Btu per Passenger-Mile			CO_2 Emissions		
	Low	Average	High	Low	Average	High	Low	Average	High
Motorcoach	190.8	195.3	200.9	690.4	710.2	726.9	51.1	52.6	53.8
Passenger Car	24.4	25.3	62.1	2,233.5	5,482.2	5,684.4	165.4	406.1	421.0
Passenger Car—TNC (0.85-Person)	20.7	21.5	52.8	2,626.9	6,451.2	6,700.5	194.6	477.8	496.3
Passenger Car—Car Pool (2-Person)	48.8	50.6	124.2	1,116.7	2,741.1	2,842.2	82.7	203.0	210.5
Commuter Rail	6.4	36.88	80.0	1,733.8	3,760.8	21,671.9	128.4	278.6	1,605.2
Demand Response	0.5	6.12	29.3	4,733.8	22,663.4	277,400	350.6	1,678.7	20,547
Ferry Boat	1.1	7.38	18.0	7,705.6	18,794.0	126,091	570.8	1,392.1	9,339.6
Heavy Rail	7.1	88.72	150.9	919.2	1,563.3	19,535.2	68.1	115.8	1,447.0
Intercity Rail (Amtrak)		56.0[2]			2,476.8			183.5	
Light Rail	3.5	47.42	129.6	1,070.2	2,924.9	39,628.6	79.3	216.7	2,935.3
Transit Bus[1]	2.3	18.77	67.4	2,057.9	7,389.5	60,304.3	152.4	547.3	4,466.8
Trolley Bus	20.2	47.21	72.8	1,905.2	2,937.9	6,866.3	141.1	217.6	508.6
Vanpool	17.7	97.36	161.9	856.7	1,424.6	7,836.2	63.5	105.5	580.4

[1]For transit buses, Bus (Mode=MB) and Bus Rapid Transit (Mode=RB) were considered the same (i.e., the minimum passenger-miles per DGE was the minimum of the combined MB and RB modes).
[2]Passenger-miles per DGE for Amtrak's intercity rail was the weighted average of the values in Section 2.3.

On a per passenger-mile basis, ferry boats and demand response vehicles were the most energy-intensive and CO_2-emitting transportation modes. Although vanpooling ranked second best in terms of energy efficiency and CO_2 emissions among all transportation modes, vanpooling was found to use more energy and produce 2.6 times more CO_2 per passenger-mile as motorcoaches. Two-person carpooling, Amtrak's intercity rail, and single-person passenger cars emitted 3.9, 3.5, and 7.7 times more CO_2 on a per passenger-mile basis than motorcoaches, respectively.

On average, TNCs were less energy efficient than single-person commuting, using 6,451 Btu and emitting 478 g of CO_2/passenger-mile. The average TNC only generates 0.85 passenger-miles/vehicle mile driven compared to 1 passenger-mile/vehicle mile driven for single-person commuting (see Section 2.6).

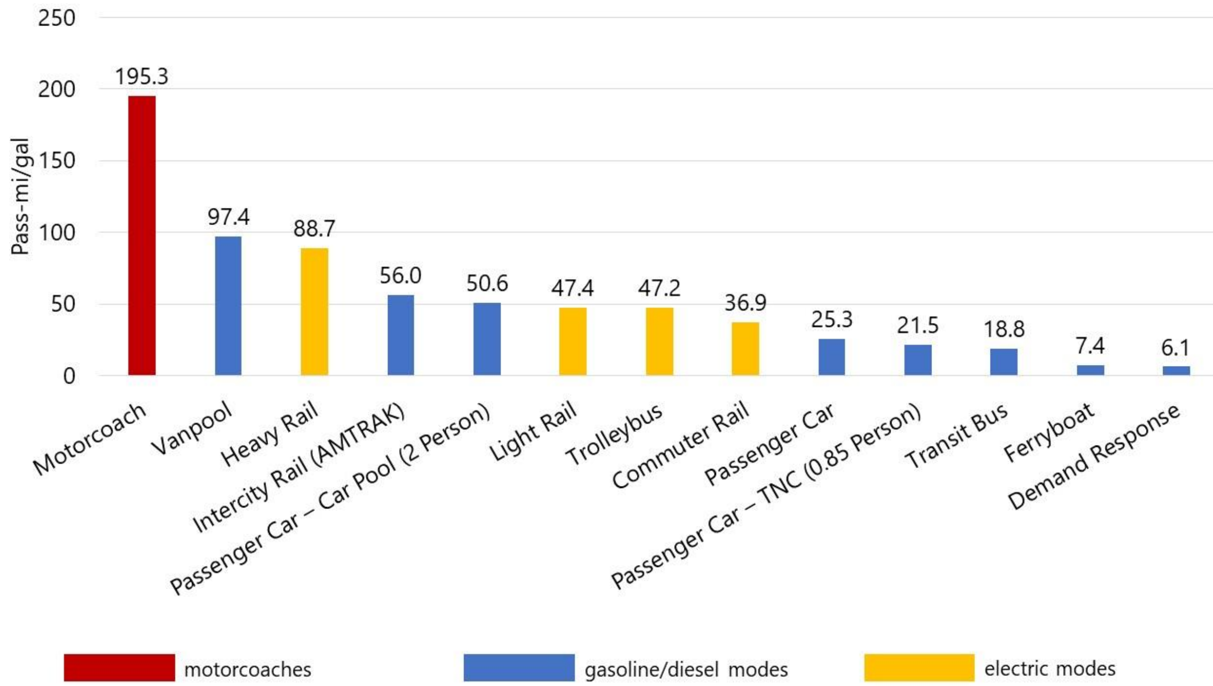

Figure 1. Passenger-Miles per DGE by Mode

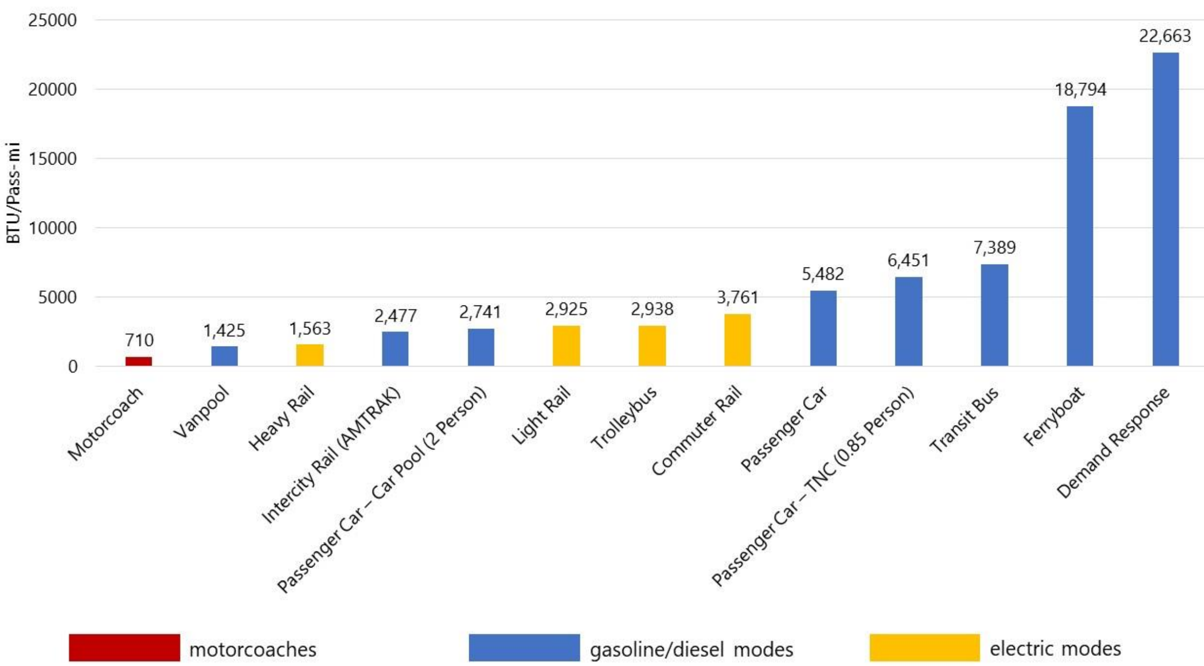

Figure 2. Energy Use (Btu) per Passenger-Mile by Mode

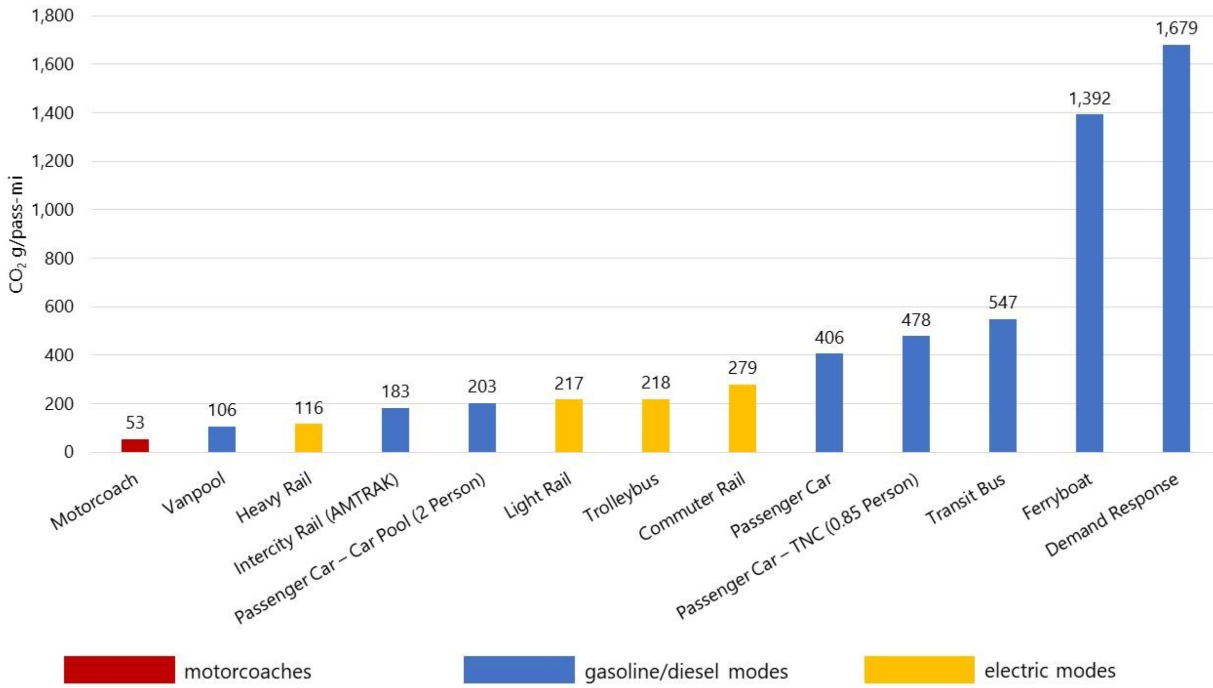

Figure 3. CO_2 Emissions (g) per Passenger-Mile by Mode

Figure 4 shows the range of energy use, and Figure 5 shows the range of CO_2 emissions for motorcoaches, vanpools, carpools, and commuter rail. As shown, the energy consumption and CO_2 emissions per passenger-mile were very consistent for motorcoaches, with a spread of less than 40 Btu/passenger-mile and 3 g of CO_2/passenger-mile between the minimum and maximum values. Conversely, vanpools and commuter rail had significant variations in energy consumption and CO_2 emission rates (as evidenced by the large disparities in minimum, average, and maximum values) based on the operator and fleet location. For carpooling, energy consumption and CO_2 emissions was highly dependant on the vehicle type; reflecting the minimum values, the hybrid vehicle consumed considerably less energy and emitted considerably less CO_2 than the average U.S. fleet vehicle.

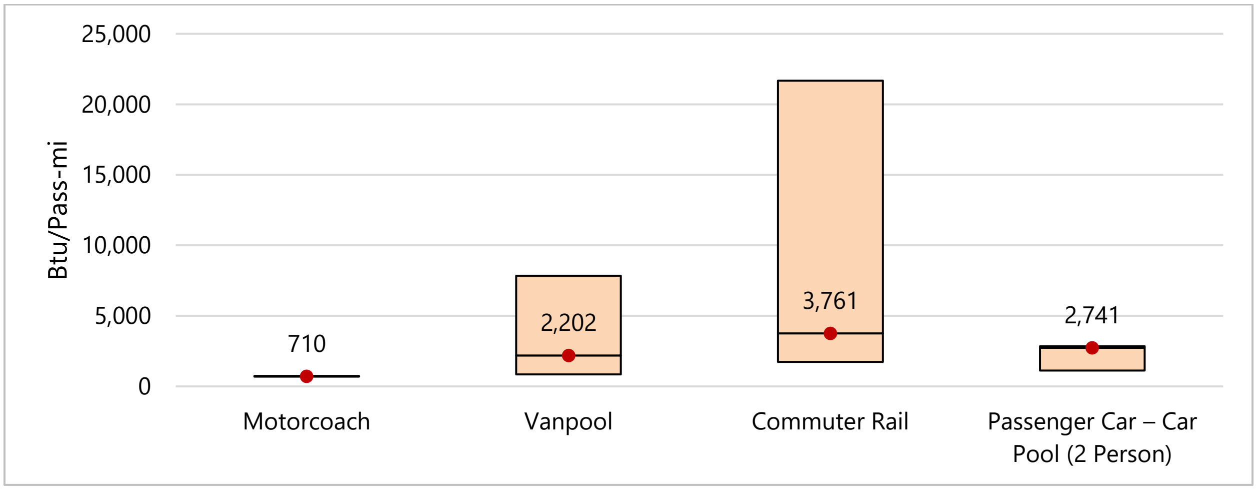

Figure 4. Range of Energy Use (Btu) per Passenger-Mile for Selected Modes

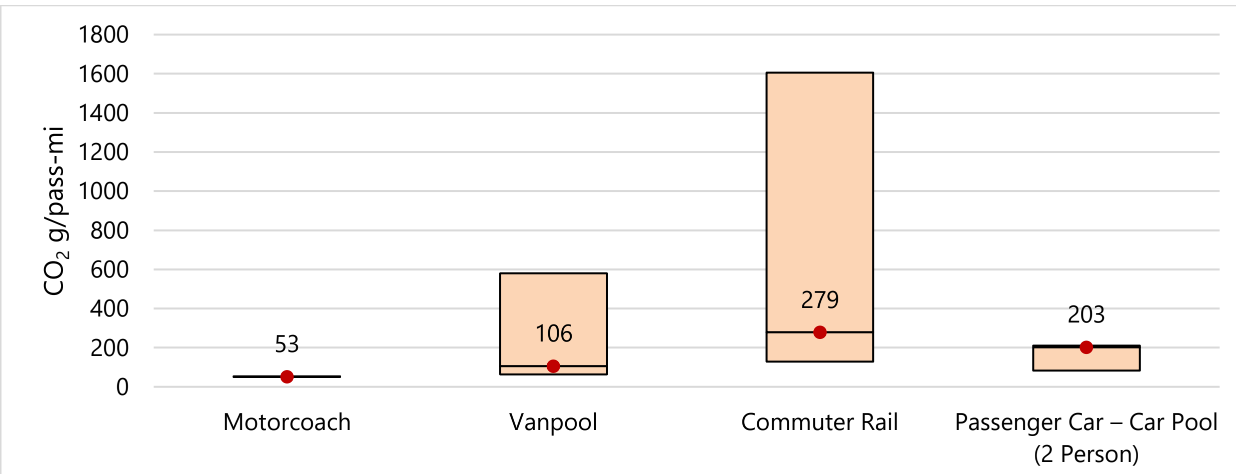

Figure 5. Range of CO_2 Emissions (g) per Passenger-Mile for Selected Modes

4.2 NO_X AND PM EMISSIONS

4.2.1 Methodology

For on-road vehicles/modes powered by diesel fuel and gasoline, NO_x and PM emissions per passenger-mile were calculated using the following equation:

$$\text{Emissions}\left(\frac{\text{g}}{\text{pass}-\text{mi}}\right) = \text{Emissions Rate}\left(\frac{\text{g}}{\text{mi}}\right) \text{x} \frac{\text{mi}}{\text{DGE}} \div \frac{\text{Pass}-\text{mi}}{\text{DGE}}$$

Information on miles per DGE that was available in existing datasets or documents (refer to Chapter 2) was prioritized over calculations. If no information was available, then the miles per DGE was calculated using the values for the average passenger-miles per DGE and the average passengers on board listed in Table 2. For example, the average passenger-miles per DGE and the average passengers on board trolley buses were 47.21 mile/DGE and 6.4 passengers, respectively. Thus, the average mile per DGE was calculated by dividing 47.21 miles/DGE by 6.4 passengers, resulting in 7.4 miles/DGE.

For the demand response mode, the 2021 Fuel and Energy dataset [4] indicated that gasoline or natural gas vehicles accounted for about 71 percent of the vehicle miles traveled by demand response vehicles. Diesel or other fuel vehicles accounted for about 29 percent of the vehicle miles traveled by demand response vehicles. Thus, for this mode, average emissions were calculated using the following equation:

$$\text{Emissions}\left(\frac{\text{g}}{\text{pass} - \text{mi}}\right) = \left(0.29 \text{ x Diesel}\left(\frac{\text{g}}{\text{pass} - \text{mi}}\right)\right) + \left(0.71 \text{ x Gasoline}\left(\frac{\text{g}}{\text{pass} - \text{mi}}\right)\right)$$

For nonroad vehicles/modes powered by diesel fuels, NO_x and PM emissions per passenger-mile were calculated using the following equation:

$$\text{Emissions}\left(\frac{\text{g}}{\text{pass} - \text{mi}}\right) = \text{Emissions Rate}\left(\frac{\text{g}}{\text{DGE}}\right) \div \frac{\text{pass} - \text{mi}}{\text{DGE}}$$

For vehicles/modes powered by electricity, NO_x and PM emissions per passenger-mile were calculated using the following equation:

$$\text{Emissions}\left(\frac{\text{g}}{\text{pass} - \text{mi}}\right) = \text{Emissions Rate}\left(\frac{\text{g}}{\text{kWh}}\right) \text{x } 40.45\frac{\text{kWh}}{\text{DGE}} \div \frac{\text{pass} - \text{mi}}{\text{DGE}}$$

Commuter rail and intercity rail (Amtrak) vehicles can be powered by either electricity or diesel. Based on the 2021 Fuel and Energy dataset [4], the passenger-miles for electric propulsion commuter rail accounted for 89 percent of all passenger-miles; diesel or other fuels accounted for another 11 percent. As discussed in Section 2.3, 73.6 percent of Amtrak's intercity rail vehicles were assumed to be diesel, while 26.4 percent of rail vehicles were assumed to be electric. For these modes, average emissions were calculated using the following equation:

$$\text{Emissions}\left(\frac{\text{g}}{\text{pass} - \text{mi}}\right) = \left(\%\text{ Diesel x Diesel }(\text{g/pass} - \text{mi})\right) + \left(\%\text{ Electricity x Electricity }(\text{g/pass} - \text{mi})\right)$$

4.2.2 Emissions Calculation

Like the 2019 report, the TTI team assumed that all passenger cars and vanpool vehicles were powered by gasoline and that all transit buses and motorcoaches were powered by diesel fuel. Table 11 lists the NO_x and PM emissions by transportation mode.

Table 11. NO_x and PM Emissions by Mode

Transportation Mode	Fleet Age	Fuel/Energy Content (%)	Miles per DGE[1]	Passenger-Miles per DGE	NO_X Emissions (g/1,000 passenger-miles)	PM_{10} Emissions (g/1,000 passenger-miles)	$PM_{2.5}$ Emissions (g/1,000 passenger-miles)
Motorcoach	MY 2021	Diesel/100	5.58	195.28	66.1	5.9	0.8
Motorcoach	2021 Fleet Average	Diesel/100	5.58	195.28	178.1	11.7	6.6
Passenger Car	MY 2021	Gasoline/100	25.30	25.30	22.0	33.3	5.4
Passenger Car	2021 Fleet Average	Gasoline/100	25.30	25.30	184.0	35.6	7.5
Passenger Car—TNC (0.85-Person)	MY 2021	Gasoline/100	25.30	21.51	25.9	39.2	6.4
Passenger Car—TNC (0.85-Person)	2021 Fleet Average	Gasoline/100	25.30	21.51	216.5	41.9	8.8
Passenger Car—Car Pool (2-Person)	MY 2021	Gasoline/100	25.30	50.60	11.0	16.7	2.7
Passenger Car—Car Pool (2-Person)	2021 Fleet Average	Gasoline/100	25.30	50.60	92.0	17.8	3.8
Vanpool	MY 2021	Gasoline/100	20.71	97.36	4.9	7.6	1.3
Vanpool	2021 Fleet Average	Gasoline/100	20.71	97.36	59.8	8.3	1.9
Transit Bus	MY 2021	Diesel/100	2.80	18.77	273.1	16.9	2.6
Transit Bus	2021 Fleet Average	Diesel/100	2.80	18.77	459.4	21.2	6.8
Demand Response	MY 2021	Gasoline/71 Diesel/29	6.80	6.12	163.6	42.3	7.2
Demand Response	2021 Fleet Average	Gasoline/71 Diesel/29	6.80	6.12	891.5	68.3	31.1
Ferry Boat	2022	Diesel/100	0.11	7.38	3,490.7	83.8	81.2
Air	2023	Diesel/100	0.57	59.28	59.2	6.9	6.2
Commuter Rail	2020	Diesel/11 Electric/89	2.84	36.88	1,450.2	56.2	51.4
Intercity Rail (Amtrak)	2020	Diesel/73.6 Electric/26.4	0.47 (Diesel) 0.77 (Electric)	47.8 (Diesel) 79.0 (Electric)	1,163.8	41.2	39.5
Heavy Rail	2020	Electric/100	7.46	88.72	136.8	11.4	9.6
Light Rail	2020	Electric/100	4.94	47.42	255.9	21.3	17.9
Trolley Bus	2021	Electric/100	7.38	47.21	257.0	21.4	18.0

[1]Miles per DGE for the TNC, car pool, vanpool, transit bus, demand response, ferry boat, commuter rail, heavy rail, light rail, and trolley bus modes were calculated using average passenger on board information (see Table 2).

As shown in Figure 6 through Figure 8, the existing fleet of motorcoaches produced, on average, about 178 g of NO_x, 12 g of PM_{10}, and 7 g of $PM_{2.5}$ per 1,000 passenger-miles. The motorcoach emissions were consistently under the average for all vehicle types. Only the vanpool and domestic aircraft modes consistently performed better than motorcoaches in terms of NO_x and PM emissions per passenger-mile.

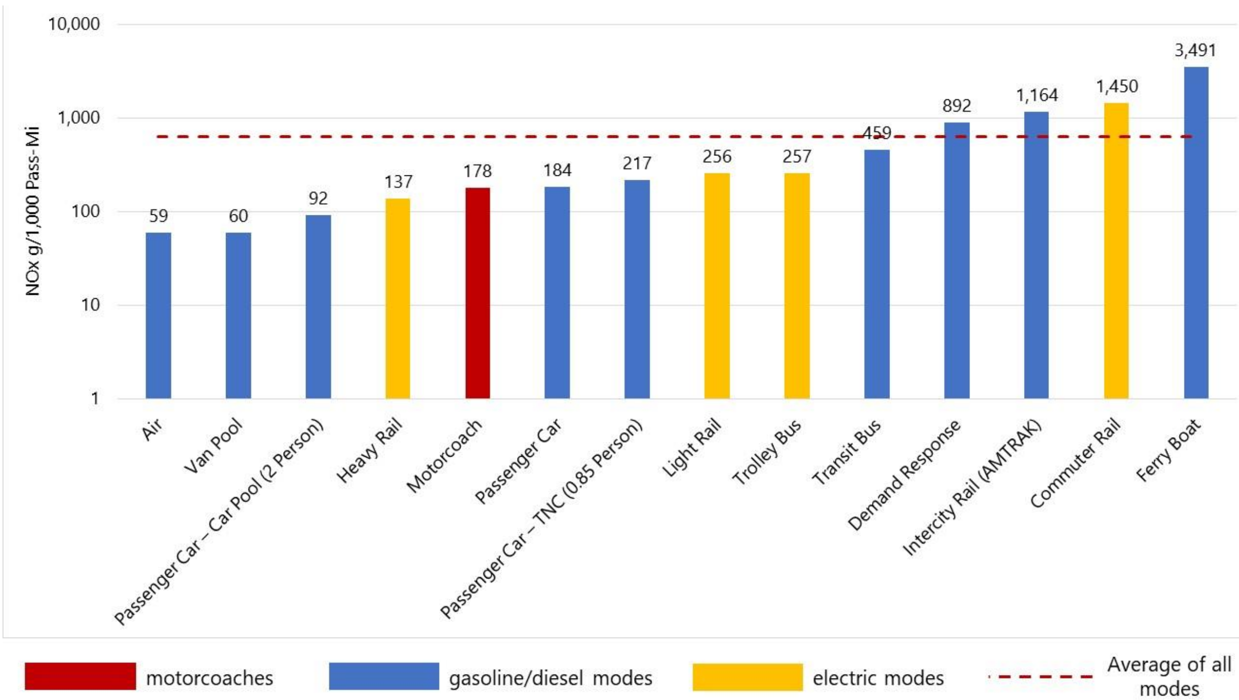

Figure 6. 2021 Fleet Average NO_x Emissions (g) per 1,000 Passenger-Miles

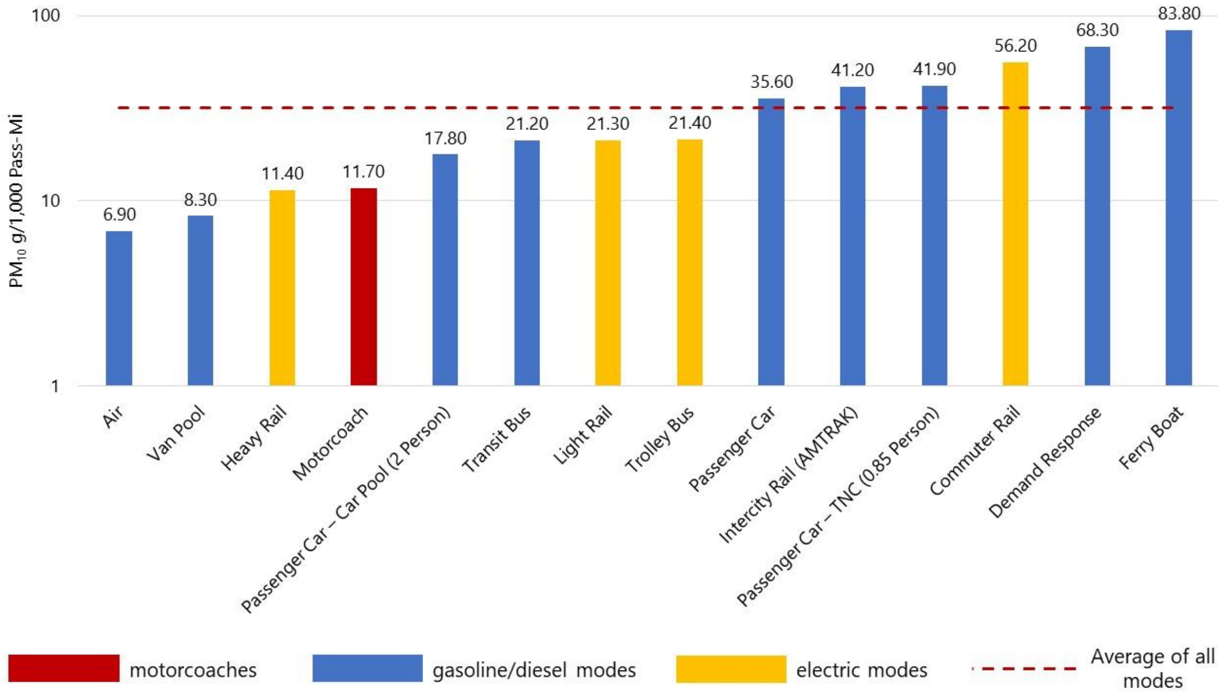

Figure 7. 2021 Fleet Average PM_{10} Emissions (g) per 1,000 Passenger-Miles

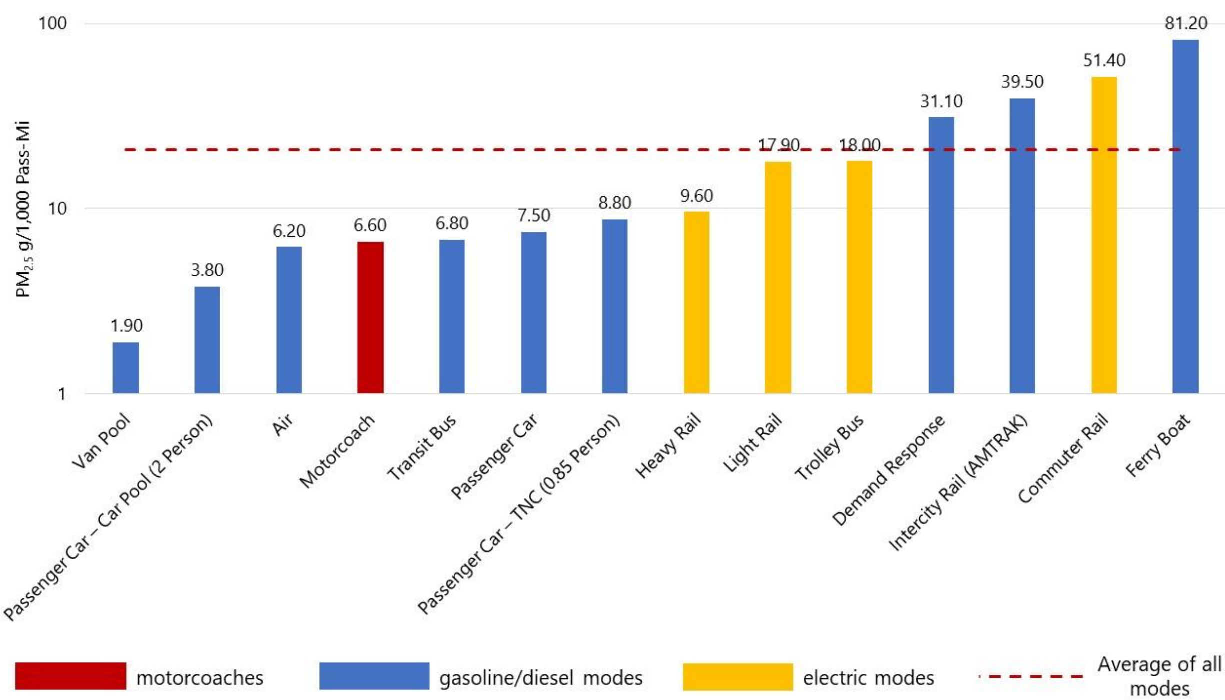

Figure 8. 2021 Fleet Average $PM_{2.5}$ Emissions (g) per 1,000 Passenger-Miles

Comparing the MY 2021 vehicles to the 2021 fleet average, the TTI team observed that emissions in the newer vehicles were substantially lower than the fleet average. For motorcoaches, the NO_x, PM_{10}, and $PM_{2.5}$ emissions from the MY 2021 vehicles were 63, 50, and 88 percent lower than the 2021 fleet average. In comparison, the NO_x, PM_{10}, and $PM_{2.5}$ emissions for the MY 2021 gasoline-powered passenger cars were 88, 6, and 28 percent lower than the fleet average. For diesel-powered transit buses, these same emissions for the MY 2021 vehicles were 41, 20, and 62 percent lower than the fleet average. While the decrease in NO_x emissions for motorcoaches was not as pronounced as the decrease for gasoline-powered vehicles, these vehicles performed much better than other on-road diesel-powered transportation modes. In contrast, the decrease in PM was higher for motorcoaches than any other on-road transportation mode.

Figure 9 through Figure 11 compare emissions for MY 2021 vehicles using emission rates derived from the latest MOVES4. Regarding NO_x emissions, gasoline-powered passenger cars and their variations (TNCs and two-person carpools), as well as vanpools (passenger trucks in the MOVES4), emitted less NO_x than motorcoaches. The NO_x emission rates in the MOVES4 were significantly lower for MY 2021 passenger cars and trucks than motorcoaches; the gasoline-powered engines of these light-duty vehicles emit less NO_x than the diesel-powered motorcoaches (see Table 9). However, motorcoaches emit substantially less NO_x compared to other diesel-powered modes such as demand response vehicles and transit buses. The MY 2021 motorcoaches also had less PM emissions per 1,000 passenger-miles than other vehicle types.

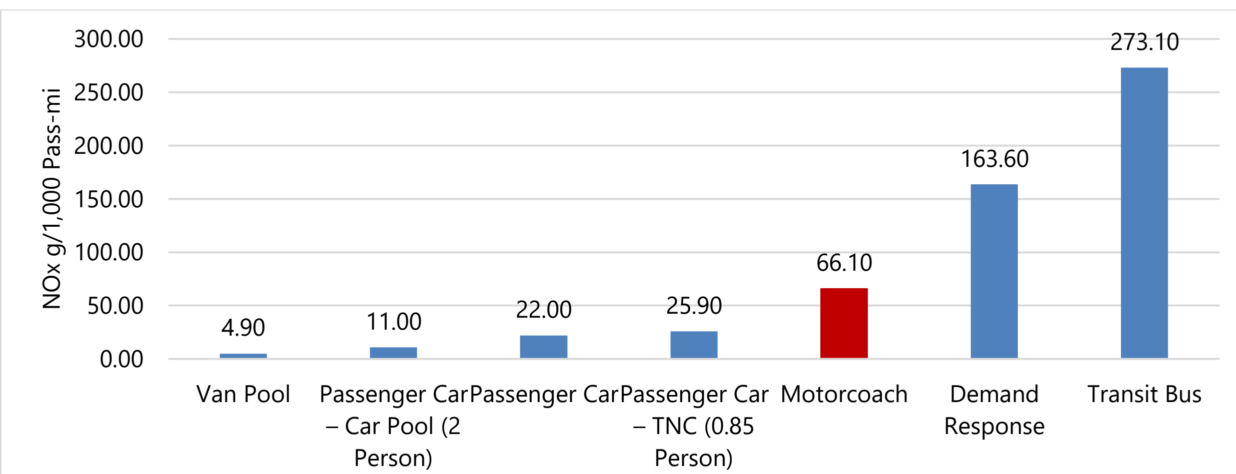

Figure 9. NO_x Emissions (g) per 1,000 Passenger-Miles for 2021 Vehicles

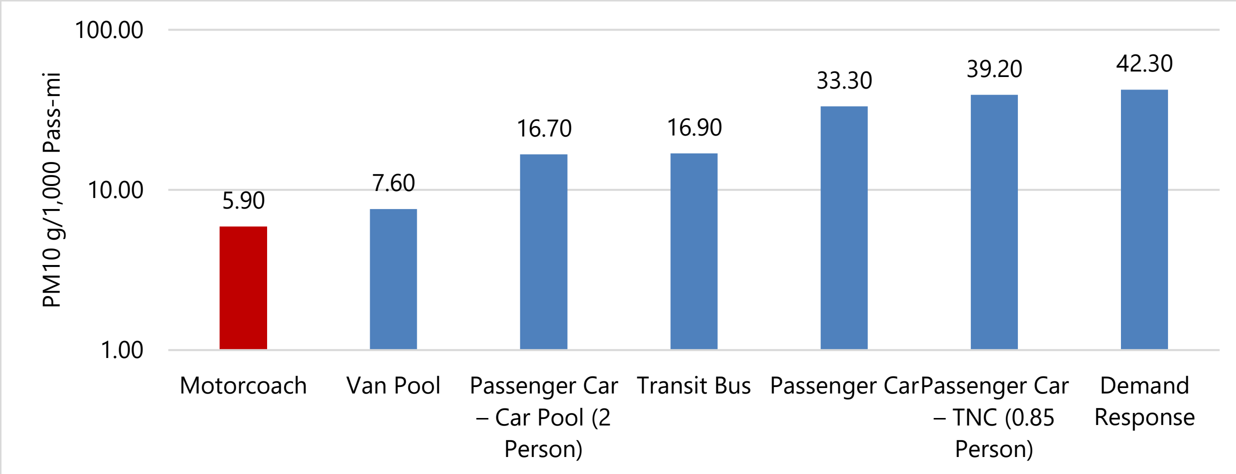

Figure 10. PM_{10} Emissions (g) per 1,000 Passenger-Miles for 2021 Vehicles

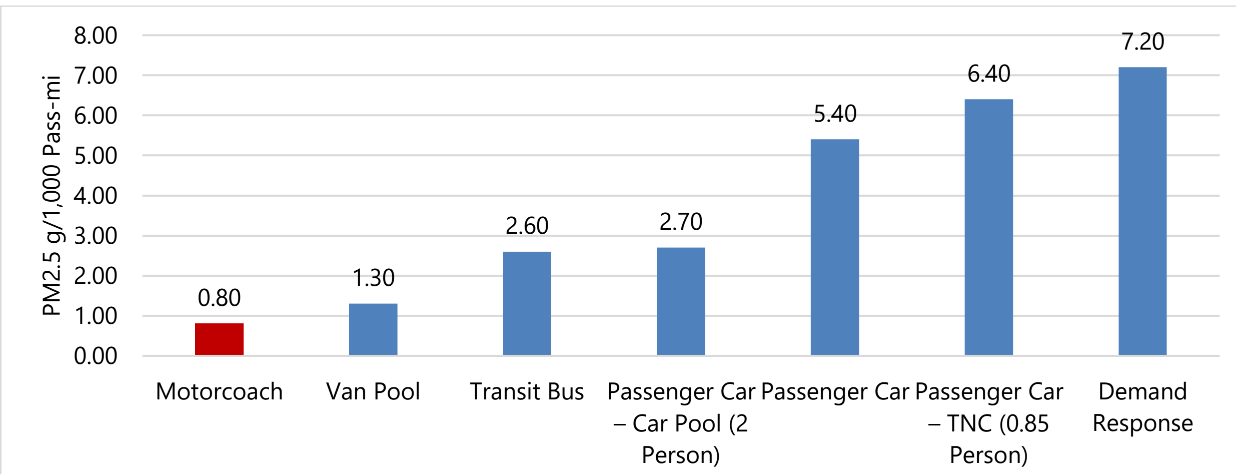

Figure 11. $PM_{2.5}$ Emissions (g) per 1,000 Passenger-Miles for 2021 Vehicles

To summarize, as evidenced from a comparison of the 2021 fleet average to the MY 2021 values, motorcoach PM emissions per 1,000 passenger-miles improved significantly, moving from being ranked 4th or 5th to being the most emission-efficient among the transportation modes. In addition, while the decrease in NO_x emissions was not as high as the gasoline-powered transportation modes, motorcoach NO_x emission rates showed very substantial improvements when comparing the MY 2021 rates to the fleet average. Thus, as more new vehicles enter the fleet and displace current vehicles, the emissions per passenger-mile from motorcoaches, especially for PM, are expected to decrease even further.

5 QUALITY ASSURANCE/QUALITY CONTROL

This chapter provides a summary of the TTI team's QA/QC process for the results of this study. It is divided into two sections—the first discusses the QA/QC for fuel use and passenger-miles, and the second discusses the QA/QC for emission rates (as derived from the MOVES4, obtained directly from the literature review, and/or calculated).

5.1 FUEL USE AND PASSENGER-MILES

5.1.1 Number of Agencies and Vehicles

Table 12 shows the number of agencies and vehicles from the 2017 and 2021 [4] Fuels and Energy datasets, which were utilized in the 2019 report and this study, respectively. Note that the TTI team was unable to reproduce the number of agencies and vehicles for the transit bus mode that were reported in the 2019 report, even though all other transportation modes matched perfectly. The Fuels and Energy dataset does not contain a singular transit bus mode but instead includes buses and rapid bus transit. In the 2017 dataset, these combined categories sum to 311 unique agencies (in terms of NTD IDs) and 38,780 vehicles.

Table 12. Number of Agencies and Vehicles QA/QC

Transportation Mode	2017 Number of Agencies (2019 Report)	2021 Number of Agencies (This Study)	Difference (%)	2017 Number of Vehicles (2019 Report)	2021 Number of Vehicles (This Study)	Difference (%)
Commuter Rail	7	9	29	4,916	3,746	–24
Demand Response	219	216	–1	6,104	5,380	–12
Ferry Boat	12	16	33	76	84	11
Heavy Rail	14	14	0	9,479	9,448	0
Intercity Rail (Amtrak)	1	1	0	259	284	10
Light Rail	21	21	0	1,568	1,294	–17
Transit Bus	314[1]	301	–4	40,585[1]	34,399	–15
Trolley Bus	5	5	0	415	366	–12
Vanpool	39	30	–23	7,196	3,895	–46

[1]The TTI team was unable to reproduce the number of agencies or vehicles for trolley buses that was in the 2019 report using the same methodology and the same dataset.

As shown in Table 12, most of the transportation modes had lower vehicle counts in 2021 than in 2017, with the most significant decrease (46 percent) observed for vanpools. Comparing the number of agencies for each transportation mode, vanpools were again the outlier with a 23 percent decrease in the number of agencies. In contrast, the number of commuter rail and ferry boat agencies increased by 29 and 33 percent, respectively.

The TTI team downloaded the Fuel and Energy datasets from 2018 through 2020 to analyze the overall trend for the QA/QC of the dataset used in this study. Commuter rail and ferry boat agencies experienced growth from 2017 to 2021, with the highest spikes in 2018 (14 percent) for commuter rail and 2020 (15 percent) for ferry boats. On the other hand, the number of vanpool agencies has been in decline since 2017, with the largest drop occurring in 2018 with an 18 percent decrease from 39 to 34 agencies. In terms of the number of vehicles, most vehicle types saw fluctuating or constant decreases in the number of vehicles. The 2021 dataset revealed substantial drops in vehicle counts for all vehicle types. This was especially apparent for light rail, which had a slight increase until 2020 before plummeting by 21 percent in 2021. Vanpools, already on a declining trend, witnessed a sharp 40 percent drop in vehicle numbers in 2021.

The substantial drop in vehicle counts in the dataset used in this study can likely be attributed to the COVID-19 pandemic shutdowns. According to the FTA, the COVID-19 pandemic shutdowns heavily impacted this dataset because most of the data were collected at the beginning of FY 2021 on July 1, 2020 [5]. The impacts of the COVID-19 pandemic were substantial. April 2020 was the lowest month on record for public transportation ridership, and even by December 2021, the national ridership had not recovered to pre-pandemic levels [5].

5.1.2 DGE and Passenger-Miles

Table 13 compares the DGE and passenger-miles from the 2019 report with the DGE and passenger-miles used in this study, derived from the 2017 and 2021 [4] Fuels and Energy data, respectively. The QA/QC showed significant differences between the values. Note that by following the methodology outlined in Section 2.1, the TTI team was able to reproduce all values from the 2019 report, except for the transit bus and ferry boat modes. As previously discussed, in the case of transit buses, the TTI team combined the values for buses and rapid bus transit, resulting in DGE and passenger-mile values that differed from the 2019 report (455 million versus 477 million [2019 report] DGE and 14,493 million versus 16,090 million [2019 report] passenger-miles). While the TTI team successfully replicated the DGE for ferry boats in the 2019 report, the derived passenger-mile value was higher than reported (414 million versus 387 million [2019 report] passenger-miles).

Table 13. DGE and Passenger-Miles QA/QC

Transportation Mode	2017 DGE (2019 Report)	2021 DGE (This Study)	Difference (%)	2017 Passenger-Miles (2019 Report)	2020 Passenger-Miles (This Study)	Difference (%)
Commuter Rail	98,776,470	81,662,141	–17	9,583,592,438	3,011,934,483	–69
Demand Response	22,998,085	18,853,587	–18	208,127,422	115,413,818	–45
Ferry Boat	32,536,975	32,020,026	–2	413,893,420[1]	236,257,443	–43
Heavy Rail	92,027,683	83,421,718	–9	17,555,538,158	7,401,402,604	–58
Light Rail	21,811,779	18,775,349	–14	2,404,309,005	890,312,966	–63
Transit Bus	454,701,568[1]	362,236,585	–20	14,493,321,473[1]	6,799,694,379	–53
Trolley Bus	1,541,770	1,189,555	–23	140,216,422	56,164,338	–60
Vanpool	5,485,884	2,291,373	–58	587,323,853	223,083,935	–62

[1]The TTI team was unable to reproduce the DGE and passenger-mile values for transit buses that was in the 2019 report using the same methodology and the same dataset.

As shown in Table 13, while both the DGE consumed and passenger-miles were lower in 2021 than in 2017, the decreases in passenger-miles in 2021 were much more substantial than the decreases in DGE consumed. These decreases were likely due to the impacts of the COVID-19 pandemic, which substantially lowered ridership across all transportation modes [5]. The TTI team believed that the reduction in DGE consumed was not as substantial as the reduction in passenger-miles because these transportation modes likely still needed to operate despite lower ridership. The exception was vanpools, which experienced a drop in DGE consumed that was about equivalent to its drop in passenger-miles traveled. A vanpool is defined as a "transit service operating as a ridesharing arrangement, providing transportation to a group of individuals traveling directly between their homes and a regular destination within the same geographical area" [1]. Thus, it was assumed that because vanpools do not follow a fixed-route, the lower ridership directly resulted in lower VMT and subsequently lower DGE consumption.

As shown in Table 14, the motorcoach passenger-mile per DGE in this study was about 30 percent lower than the value in the 2019 report. This difference is not of grave concern because the value still falls between the 2015 and 2017 values (refer to Table 3), which correlate with the service mileage.

Table 14. Miles and Passenger-Miles per DGE QA/QC

Transportation Mode	2017 Miles per DGE (2019 Report)	2021 Miles per DGE (This Study)	Difference (%)	2017 Passenger-Miles per DGE (2019 Report)	2021 Passenger-Miles per DGE (This Study)	Difference (%)
Motorcoach	6.4	5.58	–12.8	277	195.28	–29.5
Passenger Car	25.4	25.30	–0.4	27.8	25.30	–9.0
Passenger Car—TNC (0.85-Person)	25.4	25.30	–0.4	24.1	21.51	–10.7
Passenger Car—Car Pool (2-Person)	25.4	25.30	–0.4	50.8	50.6	–0.4
Vanpool	13.2	20.71	56.9	107.1	97.36	–9.1
Transit Bus	3.3	2.80	–15.2	33.7	18.77	–44.3
Demand Response	5.1	6.80	33.3	9	6.12	–32.0
Ferry Boat		0.11		11.9	7.38	–38.0
Air		0.57		58.7	59.28	1.0
Commuter Rail		2.84		97	36.88	–62.0
Intercity Rail (Amtrak)		0.47 (D); 0.77 (E)		89.8	56.0	–37.6
Heavy Rail		7.46		190.8	88.72	–53.5
Light Rail		4.94		110.2	47.42	–57.0
Trolley Bus		7.38		90.9	47.21	–48.1

The higher drop in passenger-miles in comparison to DGE consumption from 2017 to 2021 caused an overall decrease in the passenger-miles per DGE. This trend was evident in most transportation modes (transit bus, demand response, ferry boat, commuter rail, heavy rail, light rail, and trolley bus) in the Fuels and Energy dataset, except for the vanpool mode. The passenger-mile per DGE values did not decrease as substantially for vanpools because the DGE consumed and passenger-miles traveled for vanpools decreased at a similar rate, as discussed previously. The TTI team believed the same phenomenon occurred with the Amtrak data, which experienced similar decreases in the passenger-miles per DGE.

As shown in Table 14, the only transportation modes that had passenger-miles per DGE values close to the values in the 2019 report were passenger cars (and their variants) and aircraft. In the 2019 report, the passenger-miles per DGE was higher than the miles per DGE for a single-person passenger car. The TTI team believed these values should be equal because the number of passengers is 1. The drop in TNC passenger-miles was more substantial because the average passenger per vehicle was 0.85 in this study (see Section 2.6 for more detail) compared to 0.95 in the 2019 report. Air travel passenger-miles per DGE remained relatively comparable to the 2019 report.

The 2019 report only listed miles per DGE for transportation modes whose emission rates were modeled using the MOVES. Therefore, the values for the other transportation modes could not be compared. Passenger car miles per DGE were essentially identical. Vanpool and demand response miles per DGE increased in this study, while transit bus miles per DGE decreased. The miles per DGE for these three transportation modes were calculated using the average passenger on board information from FTA's 2021 national transit summaries and trends [5] (refer to Table 2). Referring to Exhibit 16 in the 2017 national transit summaries and trends [24], the vanpool and demand response average passengers per vehicle were comparable to the 2021 values (5.6 passengers per vehicle in 2017 versus 4.7 passengers per vehicle in 2021 for vanpools and 1.1 passengers per vehicle in 2017 versus 0.9 passengers per vehicle in 2021 for demand response vehicles). However, the average passengers per vehicle for transit buses was 11.05 (MB=9, RB=17.1) in 2017 versus 6.7 (MB=5, RB=8.4) in 2021. This variation may be caused by the difference in trends for transit bus miles per DGE.

5.2 Emission Rates

The emission rates in the 2019 report differed quite substantially for several transportation modes when compared to the emission rates used in this study. This section describes the QA/QC for the emission rates.

5.2.1 On-Road Transportation Modes

Table 15 compares the emission rates used for the on-road transportation modes from the 2019 report using the MOVES2014b and 2017 data and from this study using the MOVES4 and 2017 and 2021 data.

Table 15. Comparison of the MOVES Emission Rates between Studies

Transportation Mode	Fleet Age	Fuel	MOVES2014b		MOVES4					
			2017 NO_X	2017 PM	2017 NO_X	2017 PM_{10}	2017 $PM_{2.5}$	2021 NO_X	2021 PM_{10}	2021 $PM_{2.5}$
Passenger Car	MY	Gasoline	0.05	0.0025	0.038	0.0334	0.0055	0.022	0.0333	0.0054

Transportation Mode	Fleet Age	Fuel	MOVES2014b				MOVES4			
			2017 NO_X	2017 PM	2017 NO_X	2017 PM_{10}	2017 $PM_{2.5}$	2021 NO_X	2021 PM_{10}	2021 $PM_{2.5}$
Passenger Car	Fleet	Gasoline	0.34	0.0081	0.283	0.0370	0.0087	0.184	0.0356	0.0075
Vanpool	MY	Gasoline	0.10	0.0034	0.047	0.0365	0.0065	0.023	0.0357	0.0059
Vanpool	Fleet	Gasoline	0.61	0.0100	0.520	0.0405	0.0100	0.281	0.0390	0.0087
Transit Bus	MY	Diesel	0.90	0.0160	1.821	0.1130	0.0172	1.830	0.1130	0.0172
Transit Bus	Fleet	Diesel	8.19	0.2016	4.177	0.1899	0.0917	3.078	0.1419	0.0458
Motorcoach	MY	Diesel	1.02	0.0183	2.362	0.2006	0.0291	2.315	0.2049	0.0295
Motorcoach	Fleet	Diesel	8.19	0.2016	8.716	0.5881	0.3975	6.233	0.4097	0.2295
Demand Response	MY	Gasoline	0.11	0.0035	0.061	0.0372	0.0070	0.026	0.0363	0.0063
Demand Response	Fleet	Gasoline	0.58	0.0094	0.582	0.0422	0.0113	0.258	0.0398	0.0093
Demand Response	MY	Diesel	0.44	0.0058	0.750	0.0421	0.0068	0.444	0.0423	0.0068
Demand Response	Fleet	Diesel	1.48	0.0592	3.461	0.1946	0.1479	2.135	0.1144	0.0737

For both the 2019 report and this study, the on-road emission rates were derived from the U.S. EPA's MOVES output (refer to Section 3.1). The 2019 report utilized the MOVES2014b, which was released in 2018 and was the most recent MOVES version until the release of the MOVES3 in 2020. This study utilized the most recent MOVES4, released in August 2023. To aid in the QA/QC, the TTI team also ran the MOVES4 for the 2017 analysis year to cross-check the emission rates in the 2019 report.

As shown in Table 15, the 2017 emission rates from the 2019 report and the rates derived by the TTI team using the MOVES4 substantially differed. In terms of NO_x, the MOVES4 emission rates were lower for gasoline vehicles but higher for diesel vehicles; for PM, the MOVES4 emission rates were higher across both fuel types. The TTI team deduced that these differences were the result of different input parameters and updates in the MOVES4 including the following:

- The MOVES settings used in this study were previously discussed in Section 3.1. Note that only Dallas County and the month of July were modeled in this study as a surrogate for the nationwide average.
- The U.S. EPA has reported that the average per vehicle emission rates for gasoline and diesel light-duty vehicles in the MOVES4 are higher than in previous versions. This adjustment accounts for future EV sales; under the Tier 3 and light-duty greenhouse gas rules, manufacturers can and were expected to use credits for

EVs to offset higher emissions from internal combustion engine vehicles to meet fleet emission standards [2].

- Importantly for this study, the U.S. EPA also noted that for Dallas area counties, changes in the gasoline parameter for the soon-to-be-required RFG were incorporated [2]. Based on the U.S. EPA's *Fuel Effects on Exhaust Emissions from On-Road Vehicles in MOVES3* [25], RFG yields a 6.6 percent reduction in NO_x emissions for normal emitters and an 11.2 percent reduction in NO_x emissions for Tier 0 high-emitting vehicles. The TTI team believed that the change in Dallas gasoline parameters to account for RFG explained the lower NOx emission rate in the MOVES4 2017 output.
- Compared to previous versions, the MOVES4 activity data were updated using the latest available historic FHWA data and vehicle registration data [2]. For example, the TTI team compared the distance traveled activity output for MY 2021 passenger cars in the 2021 analysis year in Travis County, Texas. The MOVES4 activity was about 3 percent higher than the MOVES3 activity, which was roughly equivalent to the MOVES2014b activity.

While the emission rates differed due to differences in the emission model structure and run specifications, the TTI team still believed the updated emission rates to be valid, developed using the most up-to-date data and models.

Comparing the MOVES4 outputs, the MY 2021 and fleet average emission rates were lower in 2021 for all transportation modes and fuel types compared to 2017. For the 2017 analysis year, the fleet MY ranged from 1987 to 2017, whereas for the 2021 analysis year, the fleet MY ranged from 1991 to 2021. The lower fleet average emission rates were the combined result of cleaner new vehicles (as evidenced by the MY-specific emission rates) and decommissioned high-polluting older vehicles. This observation further solidified the conclusion made in Section 4.2.2, which stated that the rollout of newer and the retirement of older motorcoaches will continue to reduce emissions released from the overall fleet.

5.2.2 Nonroad Transportation Modes

As shown in Table 16, the NO_x and PM emission rates for ferry boats and aircraft, as well as the PM emission rates for electric transportation modes, varied between both studies.

Table 16. Comparison of the Nonroad Emission Rates between Studies

Transportation Mode	Fuel	2019 Report		This Study		
		2017 NO_X Emission Rate	2017 PM Emission Rate	2021 NO_X Emission Rate	2021 PM_{10} Emission Rate	2021 $PM_{2.5}$ Emission Rate
Ferry Boat	Diesel	446.93	18.78	241.21	5.79	5.61
Air	Diesel	37.08	2.20	6.16	0.72	0.64
Commuter Rail	Diesel	157.00	4.20	136.78	3.76	3.65
Commuter Rail	Electric	0.235	0.05	0.3	0.025	0.021
Intercity Rail (Amtrak)	Diesel	157.00	4.20	155.21	5.23	5.07
Intercity Rail (Amtrak)	Electric	0.235	0.05	0.3	0.025	0.021
Heavy Rail	Electric	0.235	0.05	0.3	0.025	0.021
Light Rail	Electric	0.235	0.05	0.3	0.025	0.021
Trolley Bus	Electric	0.235	0.05	0.3	0.025	0.021

For ferry boats, the TTI team replaced the 20-year-old reference used in the 2019 report [18] with the U.S. EPA's report from 2022 [23]. In addition to using a more recent reference, the TTI team also weighted the emission rates by engine tier based on the emission inventories from some of the largest ports in the United States (refer to Section 3.2.4). Thus, while this study's weighted-average emission rates were substantially lower than the rates in the 2019 report, the TTI team believed that the emission rates were reasonable because the current values were retrieved directly from the U.S. EPA's most recent methodology documentation.

For aircraft, this study's emission rates were substantially lower than the rates in the 2019 report. The NO_x emission rates used in the 2020 NEI calculations were lower than the rates published in the 2000 IPCC inventories [17]. The 2000 IPCC inventories used large commercial aircraft to represent the average fleet. For comparison, the commercial aircraft NO_X emission rate in the 2020 NEI was 8.5 kg/LTO, which was not substantially lower than the 2000 IPCC inventory rate of 10.2 kg/LTO, given 20 years of technological and aviation rule advancement. Here, the TTI team believed using a weighted average across all aircraft types can produce a more accurate representation of the overall aircraft population. For PM, the 2019 report only accounted for air taxis and used the same PM_{10} emissions per LTO for both piston and turbine air taxi engines, as seen in Table 5). In this study, the TTI team took a weighted average across all aircraft types, which was more representative of the overall aircraft population.

As shown in Table 16, the PM emission rates for electric transportation modes in this study were substantially lower (approximately half) of the rates in the 2019 report. The 2019 report used emissions from the 2014 NEI (233,506.10 tons and 182,034.68 tons for PM_{10} and $PM_{2.5}$, respectively), which were more than double the emissions in the 2020 NEI. In contrast, electricity generation in 2017 was 4,035,443 thousand-MWh, which was comparable to 2020 and 2021 values [21]. Thus, the TTI team concluded that while the difference between the rates in the 2019 report and the current PM emission rates was large, the calculations were valid given the new data.

6 SUMMARY OF FINDINGS

The results of this study point toward the following key findings:

- The results in this study are consistent with the results from the 2019 report.
- On a passenger-mile per DGE basis, motorcoaches outperformed all other transportation modes modeled in terms of energy efficiency and had lower CO_2 emissions.
- The NO_x and PM emission rates per 1,000 passenger-miles for the current fleet of motorcoaches (2021 analysis year) were below average. Additionally, when looking only at the latest MY (2021), motorcoaches had the lowest PM emission rates per 1,000 passenger-miles among all other on-road transportation modes. In terms of NO_x, only the gasoline-powered modes outperformed motorcoaches.
- As older vehicles retire and newer vehicles are introduced, motorcoach NO_x and PM emissions will decline, as evidenced by a comparison of fleet averages to MY emission rates, as well as a comparison of 2017 and 2021 analysis year emission rates (refer to Section 5.2.1).

7. REFERENCES

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APPENDIX A: DEFINITIONS OF NTD MODE DESCRIPTIONS

The definitions in this appendix were taken directly from the 2019 report [1].

- **Buses (Urban Transit Bus)**—Rubber-tired passenger vehicles powered by diesel, gasoline, battery, or alternative fuel engines contained within the vehicle. Vehicles in this category do not include articulated, double-decked, or school buses.
- **Commuter Rail**—A transit mode that is an electric or diesel-propelled railway for urban passenger train service consisting of local short-distance travel operating between a central city and adjacent suburbs. Service must be operated regularly by or under contract with a transit operator to transport passengers within urbanized areas, or between urbanized areas and outlying areas. Such rail service, using either locomotive-hauled or self-propelled railroad passenger cars, is generally characterized by:
    - Multi-trip tickets.
    - Specific station-to-station fares.
    - Railroad employment practices.
    - Usually only one or two stations in the central business district.

  It does not include:

    - Heavy rail rapid transit.
    - Light rail/streetcar transit service.

  Intercity rail service is excluded, except for that portion of such service that is operated by or under contract with a public transit agency for predominantly commuter services. Predominantly commuter service means that for any given trip segment (i.e., the distance between any two stations), more than 50 percent of the average daily ridership travels on the train at least three times a week. Only the predominantly commuter service portion of an intercity route is eligible for inclusion when determining commuter rail route miles.
- **Demand Response**—Shared use transit service operating in response to calls from passengers or their agents to the transit operator, who schedules a vehicle to pick up the passengers to transport them to their destinations.

- **Ferry Boats**—Vessels for carrying passengers and/or vehicles over a body of water. The vessels are generally steam or diesel-powered conventional ferry vessels. They may also be hovercraft, hydrofoil, and other high-speed vessels.

  Intercity ferry boat service is excluded, except for that portion of such service that is operated by or under contract with a public transit agency for predominantly commuter services. Predominantly commuter service means that for any given trip segment (i.e., the distance between any two piers), more than 50 percent of the average daily ridership travels on the ferry boat on the same day. Only the predominantly commuter service portion of an intercity route is eligible for inclusion when determining ferry boat route miles.

- **Heavy Rail (Heavy Urban Rail)**—A transit mode that is an electric railway with the capacity for a heavy volume of traffic. It is characterized by:
  - High-speed and rapid acceleration passenger rail cars operating singly or in multi-car trains on fixed rails.
  - Separate rights-of-way (ROWs) from which all other vehicular and foot traffic are excluded.
  - Sophisticated signaling.
  - High platform loading.
- **Heavy Rail Passenger Cars**—Rail cars have motive capabilities and are:
  - Driven by electric power taken from overhead lines or third rails.
  - Configured for passenger traffic.
  - Usually operated on exclusive ROWs.
- **Light Rail**—A transit mode that typically is an electric railway with a light volume traffic capacity compared to heavy rail. It is characterized by:
  - Passenger rail cars operating singly (or in short, usually two-car, trains) on fixed rails in shared or exclusive ROWs.
  - Low or high platform loading.
  - Vehicle power drawn from an overhead electric line via a trolley or a pantograph.

- **Light Rail Vehicles**—Rail vehicles have motive capabilities and are:
  - Usually driven by electric power taken from overhead lines.
  - Configured for passenger traffic.
  - Usually operating on exclusive ROWs.
- **Trolley Bus (Electric Trolley Bus)**—A transit mode comprised of electric rubber-tired passenger vehicles, manually steered, and operating singly on city streets. Vehicles are propelled by a motor drawing current through overhead wires via trolleys, from a central power source not onboard the vehicle.
- **Trolley Buses**—Rubber-tired, electrically powered passenger vehicles operated on city streets drawing power from overhead lines with trolleys.
- **Vanpools**—A transit mode comprised of vans, small buses, and other vehicles operating as a ridesharing arrangement, providing transportation to a group of individuals traveling directly between their homes and a regular destination within the same geographical area. The vehicles shall have a minimum seating capacity of seven persons, including the driver. For inclusion in the NTD, it is considered a mass transit service if it is operated by a public entity, or one in which a public entity owns, purchases, or leases the vehicle(s).

  Vanpools must also comply with mass transit rules including Americans with Disabilities Act provisions and be open to the public with that availability made known. Other forms of public participation to encourage ridesharing arrangements include the:
  - Provision of parking spaces.
  - Use of high occupancy vehicle lanes.
  - Coordination or clearinghouse services.
- **Vanpool Service**—Transit service operating as a ridesharing arrangement, providing transportation to a group of individuals traveling directly between their homes and a regular destination within the same geographical area. The vehicles shall have a minimum seating capacity of seven persons, including the driver. Vanpools must also be open to the public and that availability must be made known. It does not include ridesharing coordination.