U.S. Department
of Transportation

Federal Railroad
Administration

Carbon Dioxide Emissions from Four Real World Inter-City Passenger Trips: A Comparison of Rail, Air, and Road Travel Modes by City Pair

FRA-RRD30-2022-0001

Final Report | December 2022

REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)* 12-01-2022	**2. REPORT TYPE** Technical Report	**3. DATES COVERED** *(From - To)* August 2021 – September 2022

4. TITLE AND SUBTITLE Carbon Dioxide Emissions from Four Real World Inter-City Passenger Trips: A Comparison of Rail, Air, and Road Travel Modes by City Pair	**5a. CONTRACT NUMBER** 693JJ621N000043
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) Matthew C. Simon (ORCID: 0000-0002-0924-8630), Anjuliee Mittelman (ORCID: 0000-0002-0064-2148), Gina Solman (ORCID: 0000-0002-4428-4397), Scott Gilman (ORCID: 0000-0002-5966-8377), Olivia Henning, Abigail Raymond (ORCID: 0000-0001-5158-1931), Rebecca Blatnica	**5d. PROJECT NUMBER** RR41A221
	5e. TASK NUMBER VM641
	5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) U.S. Department of Transportation John A. Volpe National Transportation Systems Center Environmental Measurement and Modeling Division Cambridge, MA 02142	**8. PERFORMING ORGANIZATION REPORT NUMBER** DOT-VNTSC-FRA-22-02
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) U.S. Department of Transportation Federal Railroad Administration Office of Railroad Development Office of Environmental Program Management Washington, DC 20590	**10. SPONSOR/MONITOR'S ACRONYM(S)** FRA
	11. SPONSOR/MONITOR'S REPORT NUMBER(S) FRA-RRD30-2022-0001

12. DISTRIBUTION/AVAILABILITY STATEMENT
This document is available to the public through the FRA website.

13. SUPPLEMENTARY NOTES
FRA Project Sponsors: Michael Johnsen, Andrea Martin

14. ABSTRACT
This study compares the operational carbon dioxide (CO_2) emissions of three main travel modes (rail, air, and road – both passenger vehicle and bus) for four real-world trips between different city pairs across the U.S. For each city pair and mode, operational emissions were estimated by calculating the roundtrip per-passenger-mile fuel efficiency and emissions. Operational emissions were bounded by emissions from the movement of passengers only (i.e., a pump-to-wheels analysis). First- and last-mile emissions for traveling to and from transit centers were calculated for five different inter-city modes. For the four scenarios analyzed, travel by car (i.e., single occupancy vehicle or SOV) or air were the most carbon intensive modes. Traveling by rail or bus was found to have substantially lower operational CO_2 emissions than either SOV or air. The electric train had the lowest CO_2 emissions of the modes compared.

15. SUBJECT TERMS
Carbon, greenhouse gas, operational emissions, transportation mode, Amtrak

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			Michael Johnsen
U	U	U	UU	38	**19b. TELEPHONE NUMBER** *(Include area code)* 202-450-8540

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18

METRIC/ENGLISH CONVERSION FACTORS

ENGLISH TO METRIC

LENGTH (APPROXIMATE)

1 inch (in) = 2.5 centimeters (cm)
1 foot (ft) = 30 centimeters (cm)
1 yard (yd) = 0.9 meter (m)
1 mile (mi) = 1.6 kilometers (km)

AREA (APPROXIMATE)

1 square inch (sq in, in^2) = 6.5 square centimeters (cm^2)
1 square foot (sq ft, ft^2) = 0.09 square meter (m^2)
1 square yard (sq yd, yd^2) = 0.8 square meter (m^2)
1 square mile (sq mi, mi^2) = 2.6 square kilometers (km^2)
1 acre = 0.4 hectare (he) = 4,000 square meters (m^2)

MASS - WEIGHT (APPROXIMATE)

1 ounce (oz) = 28 grams (gm)
1 pound (lb) = 0.45 kilogram (kg)
1 short ton = 2,000 pounds (lb) = 0.9 tonne (t)

VOLUME (APPROXIMATE)

1 teaspoon (tsp) = 5 milliliters (ml)
1 tablespoon (tbsp) = 15 milliliters (ml)
1 fluid ounce (fl oz) = 30 milliliters (ml)
1 cup (c) = 0.24 liter (l)
1 pint (pt) = 0.47 liter (l)
1 quart (qt) = 0.96 liter (l)
1 gallon (gal) = 3.8 liters (l)
1 cubic foot (cu ft, ft^3) = 0.03 cubic meter (m^3)
1 cubic yard (cu yd, yd^3) = 0.76 cubic meter (m^3)

TEMPERATURE (EXACT)

[(x-32)(5/9)] °F = y °C

METRIC TO ENGLISH

LENGTH (APPROXIMATE)

1 millimeter (mm) = 0.04 inch (in)
1 centimeter (cm) = 0.4 inch (in)
1 meter (m) = 3.3 feet (ft)
1 meter (m) = 1.1 yards (yd)
1 kilometer (km) = 0.6 mile (mi)

AREA (APPROXIMATE)

1 square centimeter (cm^2) = 0.16 square inch (sq in, in^2)
1 square meter (m^2) = 1.2 square yards (sq yd, yd^2)
1 square kilometer (km^2) = 0.4 square mile (sq mi, mi^2)
10,000 square meters (m^2) = 1 hectare (ha) = 2.5 acres

MASS - WEIGHT (APPROXIMATE)

1 gram (gm) = 0.036 ounce (oz)
1 kilogram (kg) = 2.2 pounds (lb)
1 tonne (t) = 1,000 kilograms (kg)
= 1.1 short tons

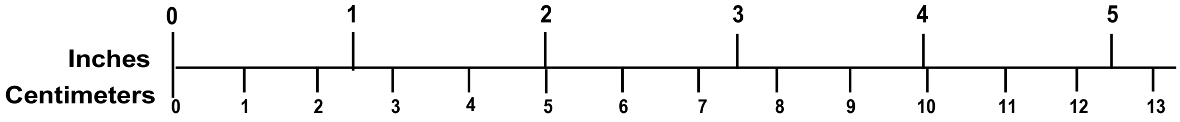
VOLUME (APPROXIMATE)

1 milliliter (ml) = 0.03 fluid ounce (fl oz)
1 liter (l) = 2.1 pints (pt)
1 liter (l) = 1.06 quarts (qt)
1 liter (l) = 0.26 gallon (gal)
1 cubic meter (m^3) = 36 cubic feet (cu ft, ft^3)
1 cubic meter (m^3) = 1.3 cubic yards (cu yd, yd^3)

TEMPERATURE (EXACT)

[(9/5) y + 32] °C = x °F

QUICK INCH - CENTIMETER LENGTH CONVERSION



QUICK FAHRENHEIT - CELSIUS TEMPERATURE CONVERSIO

°F	-40°	-22°	-4°	14°	32°	50°	68°	86°	104°	122°	140°	158°	176°	194°	212°
°C	-40°	-30°	-20°	-10°	0°	10°	20°	30°	40°	50°	60°	70°	80°	90°	100°

For more exact and or other conversion factors, see NIST Miscellaneous Publication 286, Units of Weights and Measures. Price $2.50 SD Catalog No. C13 10286

Updated 6/17/98

Acknowledgements

The authors would like to thank Christopher Witt (FRA) and Amtrak for providing ridership and diesel consumption data.

Contents

Scenario 1: Boston – New York 1

Scenario 2: Los Angeles – San Diego 2

Scenario 3: Washington – Orlando 3

Scenario 4: St. Louis – Chicago 4

Executive Summary 5

1. Introduction 6

2. Methodology 8
   - 2.1 Routes 8
   - 2.2 Ridership 8
   - 2.3 Modal CO_2 Emissions 9
   - 2.4 Last Mile CO_2 Emissions 13
   - 2.5 Scenario Emissions 14

3. Results and Discussion 15

4. Summary and Recommendations 18

5. References 20

Appendix A. Literature Review 21

Appendix B. Power Grid Assumptions 29

Abbreviations and Acronyms 30

Illustrations

Figure 1. Summary of Scenario 1 – Suitcase Full of Laundry. 1
Figure 2. Summary of Scenario 2 – Reach the Beach. 2
Figure 3. Summary of Scenario 3 – Family Disney Vacation... 3
Figure 4. Summary of Scenario 4 – Reunion in the Windy City... 4

Tables

Table 1. Summary of literature reviewed. 7

Table 2. City pair, terminal-to-terminal details by travel mode. 8

Table 3. MOVES Run Spec for passenger vehicle and transit bus CO_2 emissions by county 11

Table 4. City pair, county, and month mappings for MOVES runs 12

Table 5. Operational CO_2 emission for last-mile modes on a per-passenger-mile basis. 14

Table 6. Origin and destination points used in the full scenario analysis 14

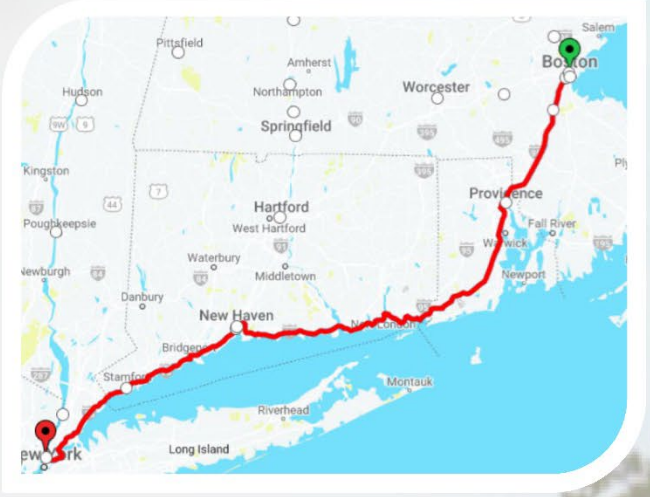
Table 7. Operational CO_2 emissions by route and mode – roundtrip emissions, terminal to terminal. 15

Table 8. Operational CO_2 emissions (total) by scenario and main mode of travel – last-mile emissions included. 16

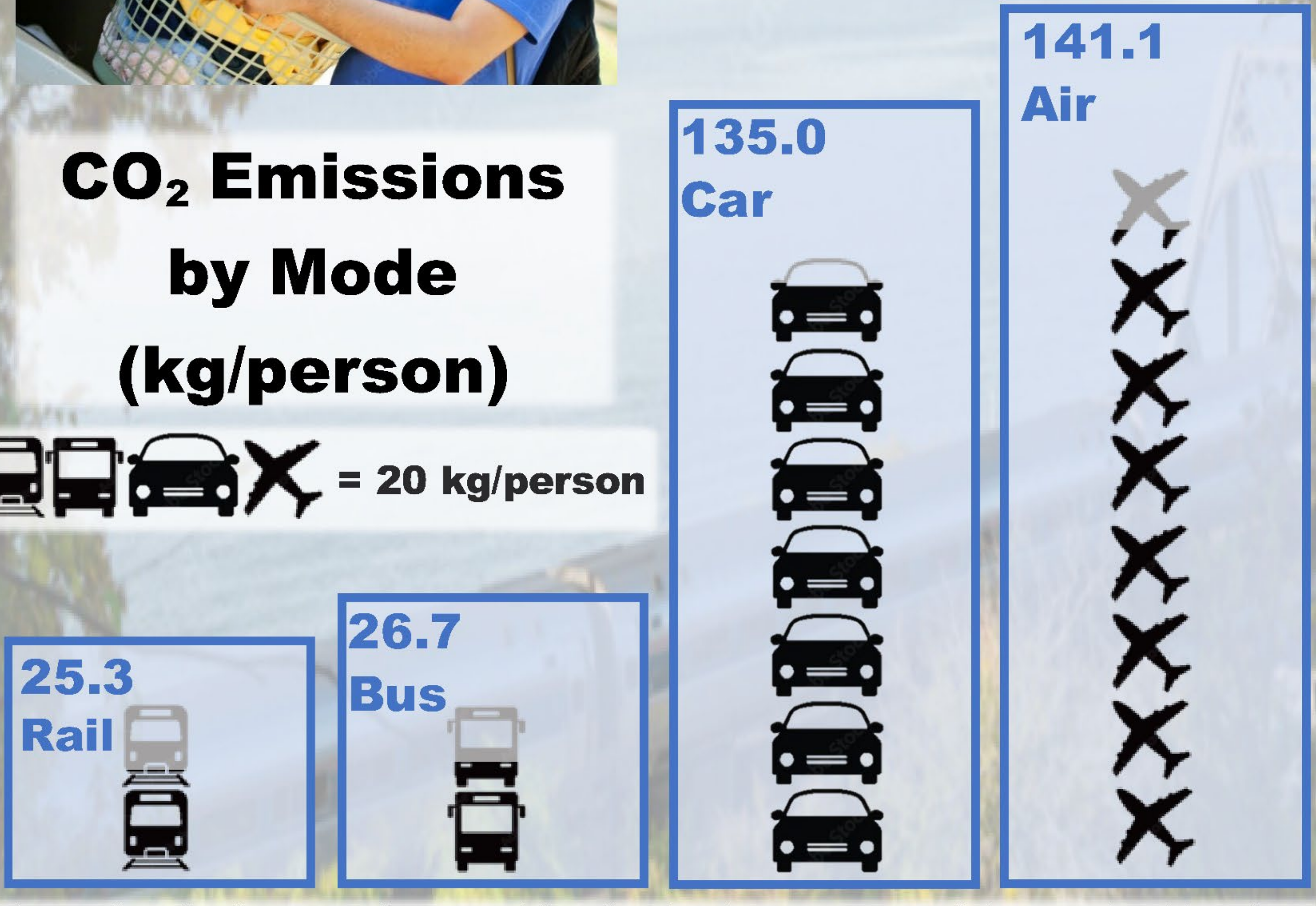
Suitcase Full of Laundry

Boston, MA → New York, NY

It's winter break at University and time for students to leave the dorms until January. For Matthew, it's a great time to pack up all the dirty laundry, get some free washing done at home, and enjoy a home-cooked meal.



The parents are treating their favorite son to a round-trip ticket on the faster, all-electric Acela from Boston to New York City, laundry and all.



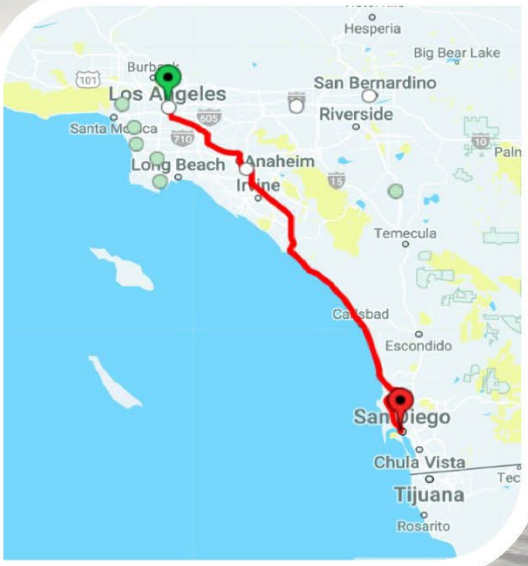
These numbers reflect the operational emissions only for each mode. Rail emission estimates include emissions from delay and idling. Please refer to the report for a more detailed analysis.

Reach the Beach

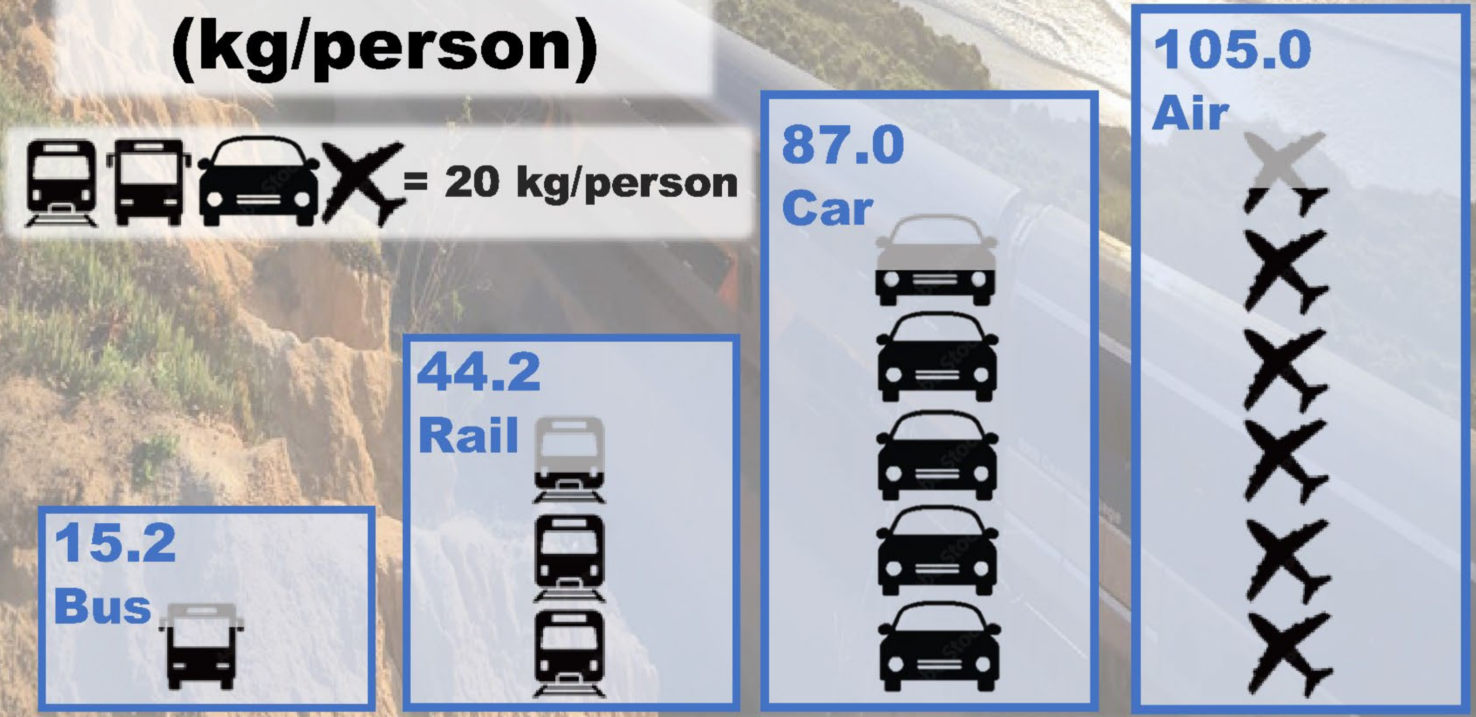
Los Angeles, CA → San Diego, CA

We won't make a call on which city has the best beaches, but the train can take you to both! Marcus, a local Santa Monica beachgoer, is hitting up Mission Beach in San Diego to mix it up for the day.

To avoid the LA traffic, Marcus decides to take the train down the coast and enjoy the beautiful scenery along the way. He even brings his surfboard along for the ride.



CO$_2$ Emissions by Mode (kg/person)



These numbers reflect the operational emissions only for each mode. Rail emission estimates include emissions from delay and idling. Please refer to the report for a more detailed analysis.

Family Disney Vacation

Washington, DC → Orlando, FL

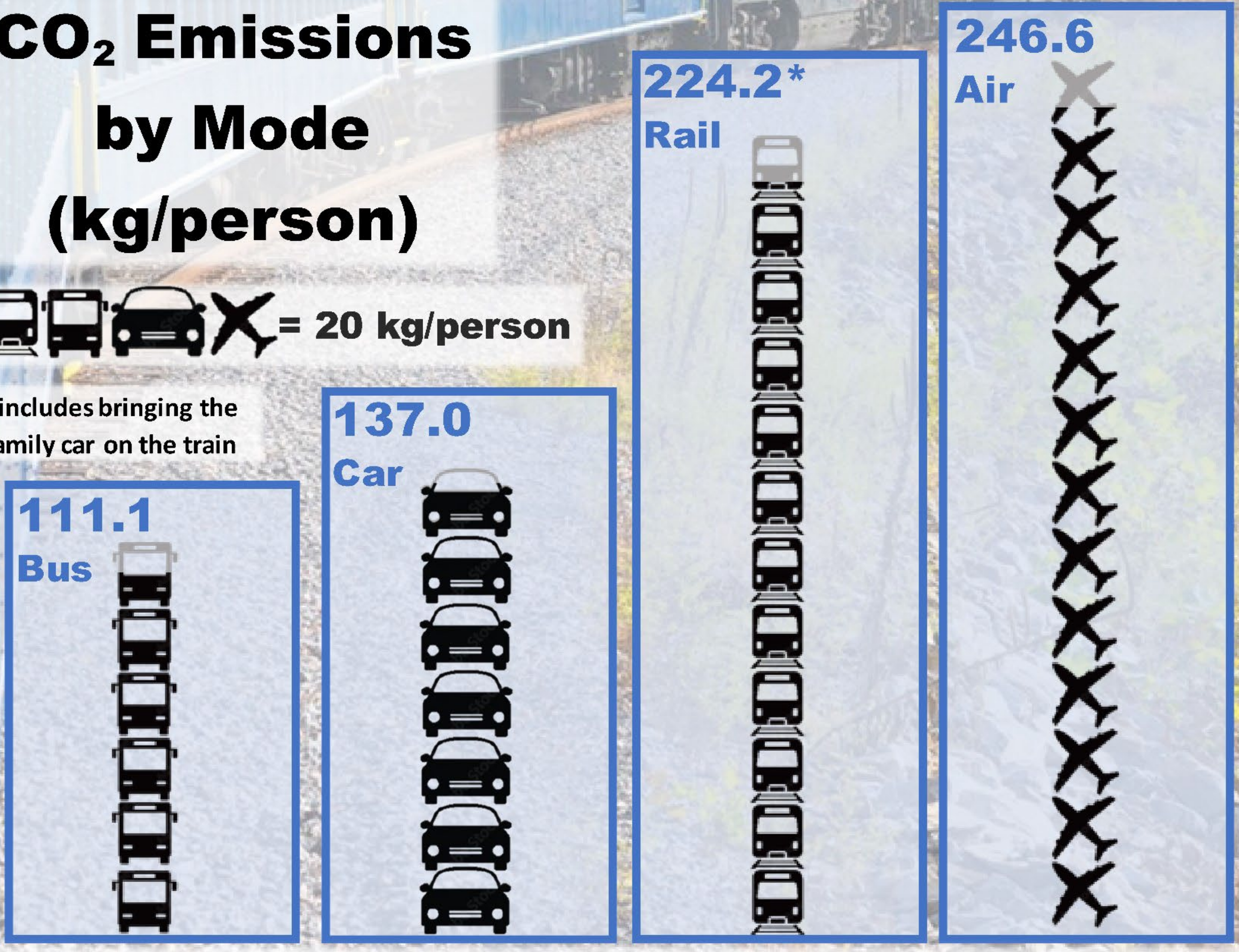
As much fun (or stressful) as driving the family to Disney World was last time, this spring break the Griswalds are taking themselves (and their car) on the Auto Train. No wear and tear on the car *or* the parents.

The family skips the drive, but the Auto Train lets them have their car, gear, and kids' car seats when they arrive.

CO$_2$ Emissions by Mode (kg/person)

🚆🚌🚗✈ = 20 kg/person

*includes bringing the family car on the train

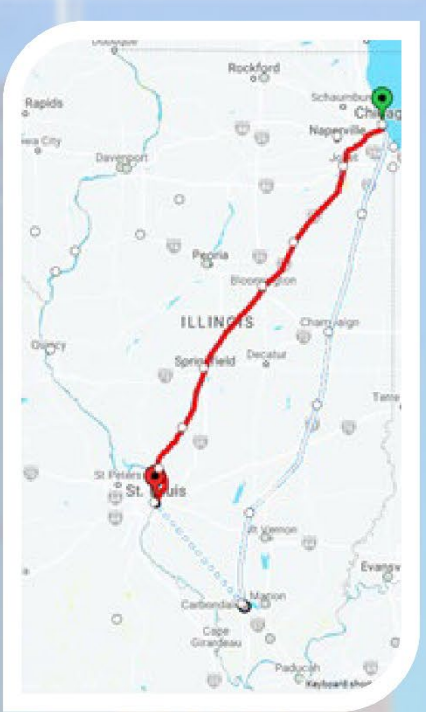


These numbers reflect the operational emissions only for each mode. Rail emission estimates include emissions from delay and idling. Please refer to the report for a more detailed analysis.

Reunion in the Windy City

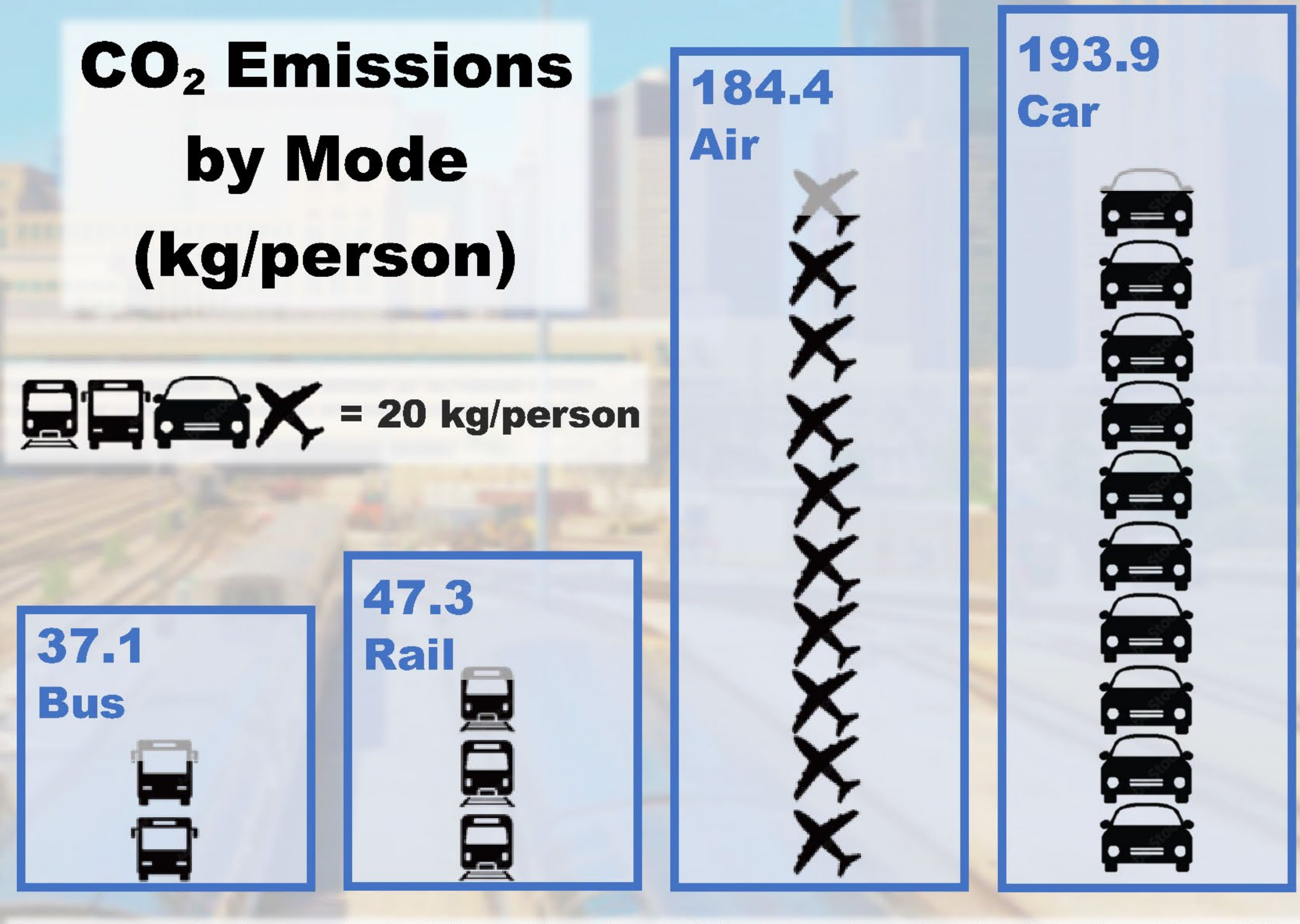
St. Louis, MO → Chicago, IL

Isabella, a professional now living in Lafayette Square in St. Louis, MO, is meeting up with some law school friends for a long weekend in Chicago, kicking it off at a local favorite steak house.



For low-stress travel and the ability to work a few extra hours en route, Isabella is taking the train there and back.

CO₂ Emissions by Mode (kg/person)



These numbers reflect the operational emissions only for each mode. Rail emission estimates include emissions from delay and idling. Please refer to the report for a more detailed analysis.

Executive Summary

This study compares the operational carbon dioxide (CO_2) emissions of three main travel modes (rail, air, and road – both passenger vehicle and bus) for four real-world trips between different city pairs across the U.S. The city pairs selected for the comparative analysis include Boston, MA – New York, NY; Los Angeles, CA – San Diego, CA; Washington, DC – Orlando, FL; and St. Louis, MO – Chicago, IL. For each city pair and mode, operational emissions were estimated by calculating the roundtrip per-passenger-mile fuel efficiency and emissions. Operational emissions were bounded by emissions from the movement of passengers only (i.e., a pump-to-wheels analysis). First- and last-mile emissions for traveling to and from transit centers were calculated for five different inter-city modes. Total emissions for one passenger making the journey described in each scenario were then calculated. For the four scenarios analyzed, travel by car (i.e., single occupancy vehicle or SOV) or air were the most carbon intensive modes. For the shorter routes, air travel resulted in higher emissions than SOV; for the longer routes, SOV produced higher emissions. Traveling by rail or bus was found to have substantially lower operational CO_2 emissions than either SOV or air. The emissions from traveling by bus were slightly better than the equivalent route by diesel train; however, the electric train (for the Boston-New York scenario) had the lowest CO_2 emissions of the modes compared and has the potential to have no CO_2 emissions if powered by 100 percent renewable energy.

1. Introduction

The transportation sector in the United States is the largest contributor to greenhouse gas (GHG) emissions.[1] The majority of carbon dioxide (CO_2) and other GHG emissions are due to the combustion of fossil fuels. Even electric vehicles are contributors when considering the GHGs released from generating the electricity and other upstream emissions such as construction and maintenance. A goal of the U.S. Department of Transportation (DOT) is to substantially reduce GHG emissions, with a target of economy-wide net-zero emissions by 2050. One simple strategy available, that requires no scientific advances or breakthroughs to reduce emissions, is shifting trips (whether people or freight) from carbon-intensive transportation modes to those that are less intensive.

As a first step in exploring how rail can contribute towards the goal of economy-wide net-zero emissions, the Federal Railroad Administration (FRA) asked the John A. Volpe National Transportation System Center (Volpe) to compare the operational CO_2 emissions of three main travel modes (rail, air, and road – both passenger vehicle and bus) for four real-world trips between different city pairs across the U.S. The city pairs selected for the comparative analysis include Boston, MA – New York, NY; Los Angeles, CA – San Diego, CA; Washington, DC – Orlando, FL; and St. Louis, MO – Chicago, IL.

While emissions models are well-established for both road and air travel – for example, U.S. Environmental Protection Agency's (EPA) Motor Vehicle Emissions Simulator (MOVES)[2] for road and the International Civil Aviation Organization (ICAO) Carbon Emissions Calculator[3] for air – equivalent estimator tools for U.S. rail are lacking. Tools do exist that estimate rail emissions, such as Argonne National Laboratory's Greenhouse gases, Regulated Emissions, and Energy use in Technology (GREET) model,[4] but emissions data may need to be updated and estimates are system wide (i.e., the full rail network).

To understand how researchers have approached estimating rail emissions compared to other travel modes, a literature search was conducted resulting in 18 recent (year 2009+) studies. These were reviewed in further detail, and 10 of the studies deemed to be the most relevant for this analysis effort are highlighted in Table 1. More detailed summaries of each are available in Appendix A. In brief, the literature search highlighted the reliance on study-specific emissions estimates over established emissions models or tools much of the time. As such, this analysis used a similar approach for rail.

The section below details the methodology used for all travel modes, including key data sources and assumptions. For the analysis to be representative of origin to destination travel scenarios, last-mile emissions were included and are also described in the methodology. This report summarizes Volpe's findings on the operational CO_2 emissions by travel mode for the four scenarios investigated.

---

[1] https://www.epa.gov/air-emissions-inventories/2017-national-emissions-inventory-nei-data.

[2] https://www.epa.gov/moves.

[3] https://www.icao.int/environmental-protection/CarbonOffset/Pages/default.aspx.

[4] https://greet.es.anl.gov/.

Recommendations for future research on GHG emissions from passenger travel are included at the conclusion of the report.

Table 1. Summary of literature reviewed.

Citation	Emissions Estimate Approach for Rail	Emissions Estimate Approach for Air	Emissions Estimate Approach for Road
(Miller, 2020)	Study-specific calculations	Emissions calculator	N/A
(Chester & Horvath, 2010)	Emissions calculator	Study-specific calculations	Study-specific calculations
(Baumeister & Leung, 2021)	Study-specific calculations	Study-specific calculations	Study-specific calculations
(Baumeister, 2019)	Study-specific calculations	Study-specific calculations	Study-specific calculations
(Graver & Frey, 2016)	Study-specific calculations	N/A	Emissions calculator
(Meynerts et al., 2018)	Emissions calculator	N/A	N/A
(Trevisan & Bordignon, 2020)	Literature review	Literature review	Literature review
(Kapetanović et al., 2019)	Literature review	N/A	N/A
(Inderbitzin, 2019)	Emissions calculator	Emissions calculator	N/A
(Dimoula et al., 2016)	Study-specific calculations	N/A	Study-specific calculations

2. Methodology

2.1 Routes

Characteristics of the four scenarios are summarized in Table 2. Route selection was based on a variety of criteria, including: 1) geographically diverse, 2) of varying distance, 3) origins and destinations were metropolitan areas with Amtrak stations, 4) include both diesel and electric Amtrak routes, and 5) at least one airport and bus station nearby to serve as a realistic travel option between the city pairs.

Table 2. City pair, terminal-to-terminal details by travel mode.

City Pair	Amtrak Station Pair	Airport Pair	Rail Distance (miles)	Air Distance (miles)*	Car Distance (miles)	Bus Distance (miles)
Boston – New York	South Station (BOS) - Moynihan Train Hall at Penn Station (NYP)	BOS – JFK	231	186	211	216
Los Angeles – San Diego	Union Station (LAX) - Santa Fe Depot (SAN)	LAX – SAN	130	109	128	112
Washington – Orlando	Auto Train Station (LOR) - Auto Train Station (SFA)	IAD – MCO	860	759	848	936
St. Louis – Chicago	Gateway Station (STL) - Union Station (CHI)	STL – ORD	284	258	300	319

*Great-circle distance – the shortest distance between two points along the surface of a sphere (e.g., Earth).

Rail and car distances were based on the route connecting the Amtrak station pairs, air distance was based on the great-circle route connecting the airport pairs, and bus distance was based on the route connecting the bus station pairs that were nearest the Amtrak stations. Road routes were the fastest, shortest routes between the stations and did not consider route modifications due to traffic conditions.

2.2 Ridership

To ensure a fair comparison across modes, the analysis assumes a single passenger for all scenarios and modes. The Washington-Orlando scenario (the Auto Train route) considered a family of four traveling together. Information about the total number of passengers (or ridership) by route assisted in the development of emission rates per passenger mile for rail. The actual ridership data (provided by Amtrak) between Amtrak station pairs for fiscal year 2019 (FY19) – the most recent year not impacted by the reduced travel demand caused by the COVID-19 pandemic – was the basis of the ridership numbers for rail. While there were other stops along the route for each of the station pairs, except for the Auto Train, where passengers would get on or off the train, only those passengers who got on at one of the station pairs and off at the other were included in this analysis.

2.3 Modal CO_2 Emissions

Different tools and approaches were used to estimate operational CO_2 emissions by mode. For this analysis, operational emissions were bounded by emissions from the movement of passengers only (i.e., a pump-to-wheels analysis). For liquid fuels, this amounts to only the CO_2 released from the fuel when combusted. For batteries or electricity from catenary lines, no CO_2 is released; however, this analysis estimated the CO_2 released during the generation of the electricity being used for motive power. The evaluation assumed current fleets and infrastructure, as well as the present-day grid mix of sources for electricity generation. Upstream emissions were not included in this analysis to portray a direct emissions scenario. However, upstream emissions from gasoline, diesel, and jet fuel are all similar and would not produce significant differences in modal comparisons.

2.3.1 Rail

Diesel

Estimated diesel usage by Amtrak service was provided by FRA and Amtrak for FY19. Amtrak uses an internal model to allocate the system-wide diesel usage to individual services based on characteristics including consist, elevation profile, and load factor. Since diesel data were for the full length of each route and passengers board/un-board from different station pairs, the average trip length for each service (data obtained from the Rail Passenger Association)[5] was used to allocate diesel on a per passenger-mile basis. Following Miller (2020), total passenger-miles traveled on each service was estimated by multiplying total ridership by the average trip length. Fuel economy by service, expressed as gallons of diesel per passenger-mile, was then calculated by dividing fuel consumption by the passenger-miles traveled. Using an emission factor of 10.16047 kg CO_2 per gallon of diesel consumed[6] it was then possible to estimate the CO_2 emissions on a per-passenger-mile basis (Equation 1).

$$E_{CO_2-service} = \frac{Diesel_{service}}{\sum Passengers_{service} * \overline{TripLength}_{service}} \times \frac{10.16047\ kg\ CO_2}{1\ gal\ diesel} \qquad [1]$$

where $E_{CO_2-service}$ is the estimated CO_2 emissions in kg/passenger-mile by Amtrak service. Total CO_2 emitted by route was then calculated by multiplying the kg CO_2 per passenger mile by the length of the route analyzed.

---

[5] Rail Passengers Association | Washington, DC - Stand Up for A Connected America!.

[6] Homepage - U.S. Energy Information Administration (EIA).

Diesel – Auto Train

Amtrak's Auto Train is a unique service that allows passengers to transport their personal vehicles as cargo, resulting in a cargo load factor that is substantially higher than other Amtrak services. As such, the Auto Train route utilized a slightly modified rail methodology than the other diesel-train routes analyzed to be able to allocate the Auto Train CO_2 emissions to both passengers and vehicles in the cargo hold, independently.

To approximate the passengers' contribution to Auto Train emissions, data from Amtrak's Silver Star service was used to estimate the fuel economy passengers only on the Auto Train. This route was assumed to be the closest approximation to passengers' fuel economy on the Auto Train because it is a long-distance route in the same region (Southeastern United States) without the added cargo of personal vehicles. Fuel economy for the Silver Star service was calculated using the data sources and methods described in Diesel. The Silver Star fuel economy was multiplied by the Auto Train's ridership to estimate total diesel used attributable to Auto Train passengers only. Total CO_2 emitted on a per-passenger-mile-only basis was found using the CO_2 per gallon of diesel emission factor.

To approximate the vehicles' contribution to Auto Train emissions, total diesel attributed to passengers only were subtracted from the total diesel used by the Auto Train. Unlike the other diesel-train service lines, Auto Train diesel used was actual diesel dispensed for locomotive operations along the route. These data were provided by Amtrak for FY19 along with total vehicle trips (broken out by cars versus motorcycles). For the purposes of estimating emissions on a per-vehicle-mile basis with no distinction between different types of vehicles, motorcycles were assumed to be one-sixth of a car. Following the same form as Equation 1, CO_2 emissions on a per-vehicle-mile basis were calculated using Equation 2:

$$E_{CO_2-vehicle} = \frac{Diesel_{AutoTrainTotal} - Diesel_{AutoTrainPassengersOnly}}{\sum Vehicles_{AutoTrain} * TripLength_{AutoTrain}} \times \frac{10.16047\ kg\ CO_2}{1\ gal\ diesel} \qquad [2]$$

where $E_{CO_2-vehicle}$ is the estimated CO_2 emissions in kg/vehicle-mile for vehicles on the Auto Train. Total CO_2 emitted by a vehicle was then calculated by multiplying the kg CO_2 per vehicle mile by the length of the Auto Train route.

Electric

Total electricity consumed by electric locomotives along the Northeast Corridor was obtained from Amtrak. Consistent with Miller (2020), it was assumed that this electricity was generated from the states through which the electric trains ran. For the Boston-New York scenario, this included: Connecticut, Delaware, Maryland, Massachusetts, New Jersey, New York, Pennsylvania, Rhode Island, and the District of Columbia. Total electricity generation and total CO_2 emissions from electricity generation for these states was obtained from EPA's Emissions & Generation Resource Integrated Database (eGRID) for 2019. These data were used to calculate the average CO_2 emissions factor [kg per kilowatt hour (kWh)] for electricity generation in these states. Fuel economy, in kWh/passenger-mile, for the Boston-New York route was estimated by dividing total electricity used by the product of station-pair ridership and route distance. Estimated CO_2 emissions was calculated by multiplying the average CO_2 emissions factor by the route's fuel economy.

2.3.2 Highway

Highway CO_2 emission rates were generated using EPA's Motor Vehicle Emissions Simulator (MOVES),[7] specifically MOVES3. MOVES is a modeling system that estimates emissions from mobile sources at the national, county, and project-levels. It provides estimates of the criteria air pollutants and GHGs, including CO_2. Specific emission rates can be developed for vehicle type, road type (rural and urban, unrestricted and restricted[8]), fuel type, and model year.

MOVES was run for each origin and destination county associated with the city pair assuming a project year of 2022. Emission rates (g/mile) were calculated for passenger vehicles and transit buses and delineated by county, road type, and month to align with each scenario. The MOVES default national mix of vehicle types, fuel types, and model years was assumed for both the passenger vehicle and transit bus fleets. The MOVES run spec parameters are summarized in Table 3.

Table 3. MOVES Run Spec for passenger vehicle and transit bus CO_2 emissions by county.

Category	Variable	Input
Description	-----	<blank>
Scale	Model	Onroad
Scale	Domain/Scale	Default Scale (uses the national database with default state and local allocation factors)
Scale	Calculation Type	Inventory
Time Spans	Time Aggregation Level	Year
Time Spans	Year	2022
Time Spans	Months	All Selected
Time Spans	Days	All Selected
Time Spans	Hours	All Selected
Geographic Bounds	-----	Cook County, IL (17031) Fairfax County, VA (51059) Los Angeles County, CA (06037) New York County, NY (36061) San Diego County, CA (06073) Seminole County, FL (12117) St. Louis City, MO (29510) Suffolk County, MA (25025)

---

[7] MOVES and Other Mobile Source Emissions Models | US EPA.

[8] Road types in MOVES include urban restricted, urban unrestricted, rural restricted, and rural unrestricted. Restricted access refers to a roadway that has been designed for high-speed traffic.

Category	**Variable**	**Input**
Vehicles/Equipment	On-Road Vehicle Equipment	Passenger Car – Diesel Fuel Passenger Car – Electricity Passenger Car – Ethanol (E-85) Passenger Car – Gasoline Passenger Truck – Diesel Fuel Passenger Truck – Electricity Passenger Truck – Ethanol (E-85) Passenger Truck – Gasoline Transit Bus – Compressed Natural Gas (CNG) Transit Bus – Diesel Fuel Transit Bus – Gasoline
Road Type	Road Types	All Selected
Pollutants and Processes	Atmospheric CO$_2$	Running Exhaust, Running Crankcase Exhaust, Start Exhaust, Crankcase Start Exhaust
Manage Input Data Series	-----	<blank>
Strategies	Rate of Progress	<blank>
General Output	Units	Mass: kilograms, Energy: Million BTU, Distance: miles
General Output	Activity	Distance Traveled
Output Emissions Detail	Always	Month, County
Output Emissions Detail	On Road/Off Road	Road Type, Source Use Type
Output Emissions Detail	For All Vehicle/Equipment Combinations	None (aggregate fleet by model year, fuel type, emission process)
Advanced Features	-----	<blank>

The specific counties and months used for each city pair are detailed in Table 4.

Table 4. City pair, county, and month mappings for MOVES runs.

City Pair	Origin County	Destination County	Month
Boston – New York	Suffolk County, MA	New York County, NY	December
Los Angeles – San Diego	Los Angeles County, CA	San Diego County, CA	August
Washington – Orlando	Fairfax County, VA	Seminole County, FL	April
St. Louis – Chicago	St. Louis City, MO	Cook County, IL	September

The output from the MOVES run was post-processed to obtain county-specific emission rates by road type and month for passenger vehicles and transit buses:

1. **Activity rates** – To obtain activity rates, vehicle miles traveled (VMT) were extracted from the results for (1) all passenger cars and trucks and (2) all transit buses by month, road type, and county.
2. **Emissions associated with VMT** – Emission rates were generated on a per-mile basis for passenger vehicles and transit buses by month, road type, and county. This involved joining emission inventories from the movesoutput table and activity from the movesactivityoutput table. Emissions were summed across all vehicle types, fuel types, and emissions processes to generate inventories for each scenario. Emission rates were calculated as an average of the origin and destination emission rates.

Additionally, it was assumed buses travel with 25 passengers,[9] which is equivalent to a load factor of 0.5 on a 50-person bus.

2.3.3 *Air*

Operational CO_2 emissions from civil aircraft were estimated with the International Civil Aviation Organization (ICAO) Carbon Emissions Calculator.[10] The ICAO Calculator estimates fuel consumption based on the great-circle distance between airport pairs and expected aircraft types flown (by route). Passenger load factors and passenger-to-cargo ratios were used to obtain the proportion of total fuel used attributable only to the passengers on board. Databases that support these CO_2 emissions estimates are updated periodically as new data are available, or on an annual basis. This includes ICAO traffic data, air carriers' schedule data, aircraft mappings (actual to model), and aircraft fuel consumption. The ICAO Calculator only estimates CO_2 emissions for aircraft operations and does not include other GHGs or emissions from maintenance, ground support equipment, or infrastructure.

2.4 Last Mile CO_2 Emissions

Last-mile CO_2 emissions considered five different modes: light rail, commuter rail, single-occupancy vehicle (SOV), city bus, and walking or biking. Emissions for the two rail modes were based on the Federal Transit Administration's Transit GHG Emissions Estimator,[11] which used data from GREET. Since emissions from the tool were on a per train basis, assumptions were made as to the average number of passengers per train to be able to estimate emissions on a per-passenger basis. For light rail, it was assumed there were 100 people per train; for the commuter rail, it was assumed there were 500 people per train. The two road modes (SOV and city bus) used MOVES to estimate CO_2 emissions. All inputs to the model were the same as reported in section 2.3.2, except the unrestricted urban roadway was used as the road type, which has higher CO_2 emissions per mile than restricted highway due to the lower speeds and more starts and stops. As with rail, an assumed number of passengers per vehicle was needed to

---

[9] DEVELOPING REFINED ESTIMATES OF INTERCITY BUS RIDERSHIP (dot.gov).

[10] ICAO Carbon Emissions Calculator.

[11] FTA's Transit Greenhouse Gas Emissions Estimator v3.0 | FTA (dot.gov).

estimate emissions on a per passenger basis. For SOV, the assumption was one; for city bus, the assumption was 15. No modeling was needed for walking or biking as CO_2 emissions for this mode are zero; electric bicycles were not considered, and neither was the potential increase in respiration (versus a person sitting on one of the other modes). Table 5 highlights the various CO_2 emission rates on a per-passenger-mile basis.

Table 5. Operational CO_2 emission for last-mile modes on a per-passenger-mile basis.

Last-Mile Mode	Emissions (kg CO_2/passenger mile)	# Passengers Assumed Per Vehicle/Train
Light Rail	0.036	100
Commuter Rail	0.056	500
Car (single occupancy)	0.383	1
City Bus	0.112	15
Walking, Biking	0.000	1

2.5 Scenario Emissions

Scenario emissions were estimated as roundtrip excursions and only considered the travel components to and from the main destination. Additional emissions while at the destination, for example, sightseeing by bus or other activities with CO_2 emissions, were not included. Last-mile emissions were added to the terminal-to-terminal emissions at both ends of the main route. It was assumed travelers went directly to the terminal from their starting point and, similarly, directly to their end-point destination from the terminal. To differentiate the higher emissions of driving on urban streets versus the highway, the terminal points for the car mode were the beginning and end of the highway segment for the overall trip. Thus, the last-mile components (with the higher emissions per mile) for traveling by car were the start-to-highway and highway-to-destination segments. For all modes, start-to-destination emissions were multiplied by two to represent the roundtrip CO_2 emissions by overall travel mode for each scenario. Last-mile emissions added to the terminal-to-terminal emissions were based on the scenario origin and destination points provided in Table 6.

Table 6. Origin and destination points used in the full scenario analysis.

City Pair	Origin	Destination
Boston – New York	Upper Residential Quad, Medford, MA	Sterling Rd., Elmont, NY
Los Angeles – San Diego	Santa Monica Blvd., Santa Monica, CA	Mission Beach, San Diego, CA
Washington – Orlando	Hackberry St., Springfield, VA	Epcot Resorts Blvd., Lake Buena Vista, FL
St. Louis – Chicago	Caroline St., St. Louis, MO	N. Rush St., Chicago, IL

3. Results and Discussion

For the four scenarios analyzed, travel by car (i.e., SOV) or air were the most carbon intensive modes. For the shorter routes, air was worse than SOV; for the longer routes, SOV was worse. Traveling by rail or bus was found to have substantially fewer operational CO_2 emissions than either SOV or air. The emissions from traveling by bus were slightly better than the equivalent route by diesel train; however, the electric train (for the Boston-New York scenario) had the lowest CO_2 emissions of the modes compared and has a high potential to produce very low or no CO_2 emissions if powered 100 percent from renewable energy. It should be noted that emissions reported for the electric train were based on the CO_2 emitted from the generation of the electricity – direct CO_2 emissions from the train are zero. For the unique scenario of traveling by Auto Train (the Washington-Orlando scenario), it was found that taking the train and bringing along one's car as cargo was less carbon intensive than driving the car. This benefit was observed even when considering two passengers traveling together (253 kg CO_2/person on the Auto Train versus 272 kg CO_2/person driving). Table 7 highlights the terminal-to-terminal roundtrip emissions for each of the four scenarios (last-mile emissions excluded), by mode.

Table 7. Operational CO_2 emissions by route and mode – roundtrip emissions, terminal to terminal.

City Pair	Car (kg CO_2/per.)	Bus[‡] (kg CO_2/per.)	Air (kg CO_2/per.)	Diesel Train (kg CO_2/per.)	Train (w/ car) (kg CO_2/per.)	Electric Train (kg CO_2/per.)
Boston – New York	132.6	24.8	129.0	N/A	N/A	23.4[+]
Los Angeles – San Diego	84.0	12.8	92.0	41.8	N/A	N/A
Washington – Orlando	543.2	107.2	237.6	175.8	330.4	N/A
Washington – Orlando (Family of 4)	135.8*	107.2	237.6	175.8	214.5*	N/A
St. Louis – Chicago	193.2	36.6	158.4	46.8	N/A	N/A

[‡] Assumes load factor of 0.5 on a 50-person bus.
[+] Emissions from electricity generation; emissions at the vehicle are zero.
*Assumes car emissions are split among four people.

For the Washington-Orlando scenario, emissions based on traveling alone versus traveling as a family of four are included. Only emissions from traveling by car or traveling by train with a car as cargo are impacted by the number of people traveling together. This is because emissions associated with the car are split across the people traveling – the more people traveling together, the fewer emissions per person. This points to why carpooling in general is a great strategy for reducing emissions. The passenger load factor is independent of the number of people traveling together by bus, air, and train (without a car). Note that air emissions for the Washington to

Orlando route do not include transporting a car as such a service is unavailable by air. Adding last-mile emissions to each of these terminal-to-terminal emissions did impact the results, but trends observed in Table 7 were largely unchanged. Total CO_2 emissions by mode and scenario (including last-mile emissions) are provided in Table 8.

Table 8. Operational CO_2 emissions (total) by scenario and main mode of travel – last-mile emissions included.

City Pair	Car[‡] (kg CO_2/per.)	Bus[+] (kg CO_2/per.)	Air[‡,+] (kg CO_2/per.)	Diesel Train (kg CO_2/per.)	Train (w/ car)[‡] (kg CO_2/per.)	Electric Train (kg CO_2/per.)
Boston – New York	135.0	26.7	141.1	N/A	N/A	25.3
Los Angeles – San Diego	87.0	15.2	105.0	44.2	N/A	N/A
Washington – Orlando	548.0	121.9	273.5	210.6	369.2	N/A
Washington – Orlando (Family of 4)	137.0*	111.1*	246.6*[+]	185.5*	224.2*	N/A
St. Louis – Chicago	193.9	37.1	184.4	47.3	N/A	N/A

[‡] Assumes last-mile mode was a car for all scenarios.
*Assumes car emissions are split among four people.
+ Air and bus service only includes passengers as air service does not allow for car transportation.

The impact to full-trip CO_2 emissions was greatest by assuming a car as the mode for the last-mile segments in each scenario. For this analysis, a car was assumed for the car, air, and train (with car) modes. For the car and train (with car) modes it was necessary for the car to be present at the beginning of the terminal-to-terminal segment of the trip, thus it was not realistic to assume any other last-mile mode in those instances. For air travel, it was assumed travelers would be seeking the fastest mode to getting from the starting point to the terminal and terminal to the end point since they had opted to fly already. It was assumed a car would be the fastest mode for all four scenarios. Additionally, for the Washington-Orlando scenario, all modes assumed a car would be rented either at the bus terminal or train station and driven to the destination. For the other three scenarios, bus and train modes assumed public transportation (i.e., city bus or light rail) in combination with some walking as the last-mile modes.

This analysis includes a few assumptions and limitations. First, the analysis did not consider the impact on emissions due to traffic or other delays (e.g., aircraft departure delays and subsequent queueing emissions). Other scenarios were also excluded, such as indirect travel routes, which would increase the total trip distance and thus total CO_2 emissions. While these complexities would be expected to increase operational CO_2 emissions and may be more representative of typical travel conditions, it was unclear what the equivalent delays are between modes and how to compare different indirect routes that still allowed the comparison by mode to be fair. As such, only unimpeded travel by different modes were included in this analysis. However, since the rail analysis was based on fuel-use data, enroute delays were included by default, which would result in slightly higher emissions as compared to air and road travel modes. Second, both rail and air modes excluded emissions related to ground support during loading and unloading. For passenger-only related emissions (i.e., passenger cargo), these emissions are expected to be low and would not change the overall emissions trends observed. For cases with freight movement mixed with passenger travel, as is often the case with larger airplanes, these emissions would likely be more substantial ground support emissions; however, freight emissions were already excluded from the analysis. Third, for air travel specifically, aircraft emissions from taxiing were also excluded.

Thus, air emissions reported by scenario are likely underestimates of the true CO_2 emissions due to air travel. This is a limitation of using the ICAO Calculator; however, its accuracy for the flight portions of each route still supported its use and are the bulk of the operational emissions. Some have reported taxi emissions can be estimated as a percentage of fuel burn on the full flight, with an average of approximately 6 percent. It was unclear how applicable this estimate would be for the eight airports included in this analysis. Instead of adding a fixed 6 percent to the estimates reported at the risk of the addition being in error, it was decided to only report CO_2 emissions as estimated by the ICAO Calculator.

This analysis also excluded upstream emissions from the production, transport, and distribution of aviation and motor vehicle fuels. Upstream emissions were included in the case of the Acela route to determine emissions from the electricity used to move the train. Upstream emissions can vary as a percentage of overall fossil fuel emissions and is largely dependent on the source of the fossil fuel.[12] The source of the oil itself tends to dictate the upstream emissions more than the refined end product, thus upstream emissions would be relative to the amount of fuel used, and thus be comparable percentages between the modes.

---

[12] Upstream Emissions as a Percentage of Overall Lifecycle Emissions | World Resources Institute (wri.org), 2016.

4. Summary and Recommendations

This analysis was a first step in exploring the role rail can play in achieving U.S. DOT's goal of economy-wide net-zero emissions by 2050, including the specific strategy of reducing GHG emissions from the transportation sector. The evaluation assumed current fleets and infrastructure and the present-day grid mix of sources for power generation, and only considered the impact of passengers traveling by different modes to the same destinations. Even within this limited scope, it is evident that rail can play a significant role in reducing operational CO_2 emissions in the U.S., where policies and programs that promote shifts to less carbon intensive modes could tap into this existing potential right now.

While shifting passenger travel from road and air to rail would reduce GHG emissions, it is important to realize traveler decision making when it comes to mode switch is complex. There are several factors that a person may consider when opting to drive instead of taking the train besides impact on the environment – travel time, cost, accessibility, convenience, among others. To fully understand the potential rail can play on reducing GHGs in the U.S., cost-benefit analyses could consider these other decision-influencing factors at a personal level. Additionally, more accurate representations of the true travel experience should be included in the analysis. For example, traveling by road through high-traffic corridors or in urban environments with lots of starts and stops, or connecting flights and trains. Not only could these real-life experiences amplify or dampen the potential GHG savings, but they could also feed into a person's decision to take one mode over another.

Shifting to less carbon intensive modes with present-day fleets and infrastructure can have immediate benefits, but to understand where the true GHG savings are in the transportation sector, the full lifecycle of each mode should be considered. This includes, but is not limited to, emissions from the construction and maintenance of infrastructure, supporting equipment (e.g., baggage tractors at airports and train stations), manufacture of vehicles (for any mode), fuel production or electricity generation, and the recycling or disposal of vehicles and infrastructure at the end of life. Sensitivity analyses may be conducted to understand how alternative fuels (e.g., biofuels and hydrogen) and use of renewable technologies for power generation (e.g., wind and solar), or new technologies (e.g., battery-electric or fuel cells) impact lifecycle GHG emissions by mode. Additionally, GHG goals outside of U.S. DOT, such as Amtrak's goal of 100 percent carbon-free electricity by 2030 and net-zero GHG emissions across their network by 2045, may speed up the adoption of cleaner technologies. Emerging travel modes are also worth evaluating, such as urban air mobility, the hyperloop, and high-speed electric rail in the U.S. Additionally, travel demand modeling may elucidate the potential impact these new technologies and travel options could have on transportation based GHG emissions.

Other near-future factors and changes will alter this analysis as the fuel sources and efficiency of vehicles are undergoing dramatic change. For example, Amtrak purchased Tier 4 locomotives, that, while focusing on EPA criteria emission reductions, may produce efficiencies not reflected in the 2019 data, as the locomotives only recently went into service (in the Chicago area). Air carriers are tracking fossil-fuel replacements with more sustainable aviation fuels with the goal of eliminating GHG emissions. Also, the fleet of U.S. vehicles continues to become more efficient with an increasing number of electric cars entering the mix, which could reduce GHG emissions estimates from the MOVES model. And to note, sources for electricity are increasingly coming from renewable energy sources and electrification is widely seen as the pathway for zero emissions in the transportation sector. Once all modes are using renewable fuels, the CO_2 emissions comparison would result in very small differences in CO_2 emissions. However, for the near and medium term, modal shift to rail from road and air can produce a substantial reduction in passenger GHG emissions for intercity travel.

Rail will certainly have a role to play in transitioning the U.S. to economy-wide net-zero emissions, with new technologies potentially amplifying the GHG savings operationally and over the lifecycle. Rail also has several other sustainability benefits over roadway travel including a smaller footprint, fewer resources for the production of vehicles, safety, and promoting denser, infrastructure-oriented development. Future research would help refine how best to realize rail's GHG emissions reduction potential and additional sustainability benefits.

5. References

Baumeister, S. (2019). Replacing short-haul flights with land-based transportation modes to reduce greenhouse gas emissions: The case of Finland. *Journal of Cleaner Production*, *225*, 262–269. https://doi.org/10.1016/j.jclepro.2019.03.329

Baumeister, S., & Leung, A. (2021). The emissions reduction potential of substituting short-haul flights with non-high-speed rail (NHSR): The case of Finland. *Case Studies on Transport Policy*, *9*(1), 40–50. https://doi.org/10.1016/j.cstp.2020.07.001

Chester, M., & Horvath, A. (2010). Life-cycle assessment of high-speed rail: The case of California. *Environmental Research Letters*, *5*(1), 014003. https://doi.org/10.1088/1748-9326/5/1/014003

Dimoula, V., Kehagia, F., & Tsakalidis, A. (2016). A Holistic Approach for Estimating Carbon Emissions of Road and Rail Transport Systems. *Aerosol and Air Quality Research*, *16*(1), 61–68. https://doi.org/10.4209/aaqr.2015.05.0313

Graver, B. M., & Frey, H. C. (2016). Highway Vehicle Emissions Avoided by Diesel Passenger Rail Service Based on Real-World Data. *Urban Rail Transit*, *2*(3), 153–171. https://doi.org/10.1007/s40864-016-0044-y

Inderbitzin, R. (2019). Switzerland: Railway or aviation nation? Emission saving potential from replacing air by train travel between Switzerland and Europe and the possibilities for the Swiss government to foster this mode shift. *Master Thesis Series in Environmental Studies and Sustainability Science*. http://lup.lub.lu.se/student-papers/record/8998563

Kapetanović, M., van Oort, N., Núñez, A., & Goverde, R. (2019). Sustainability of Railway Passenger Services – A Review of Aspects, Issues, Contributions and Challenges of Life Cycle Emissions. *RailNorrköping 2019*, 21.

Meynerts, L., Brito, J., Ribeiro, I., Peças, P., Claus, S., & Götze, U. (2018). Life Cycle Assessment of a Hybrid Train – Comparison of Different Propulsion Systems. *Procedia CIRP*, *69*, 511–516. https://doi.org/10.1016/j.procir.2017.11.035

Miller, C. A. (2020). Savings in per-passenger CO2 emissions using rail rather than air travel in the northeastern U.S. *Journal of the Air & Waste Management Association*, *0*(0), 1–14. https://doi.org/10.1080/10962247.2020.1837996

Trevisan, L., & Bordignon, M. (2020). Screening Life Cycle Assessment to compare CO2 and Greenhouse Gases emissions of air, road, and rail transport: An exploratory study. *Procedia CIRP*, *90*, 303–309. https://doi.org/10.1016/j.procir.2020.01.100

Appendix A.
Literature Review

Source: C.A. Miller (2020). Savings in per-passenger CO_2 emissions using rail rather than air travel in the northeastern U.S. *Journal of the Air & Waste Management Association*

Overview: This study examined 120 city pairs in the Northeastern U.S. and compared CO_2 emissions associated with air travel versus emissions from rail travel. The report compared flight emissions (calculated using the International Civil Aviation Organization (ICAO) flight emissions calculator) with Amtrak emissions calculated using the Environmental Protection Agency's (EPA) Simplified GHG Emissions Calculator.

Description of model and method development: Air travel CO_2 emissions were calculated using the ICAO Carbon Emissions Calculator. The ICAO flight emissions calculator was used to determine emissions from air travel based on flight origin and destination. The ICAO calculator estimates CO_2 mass for a single passenger on the journey, assuming one-way direct flights, economy-class, and great circle distance for each city pairs. Miller divided CO_2 mass by flight distance to determine the pounds (lb) of CO_2 emitted per passenger-mile. For rail travel, an average emission factor for electric locomotives was calculated using electricity generation by state, multiplied by the Bureau of Transportation Statistics' estimate of energy used (in kilowatt hours, or kWh) for Amtrak travel. An average emission factor for diesel locomotives was calculated using reported diesel fuel consumption and an average CO_2 per gallon diesel (i.e., 22.40 lb CO_2). The allocations of passenger miles on electrified and diesel routes were calculated using Rail Passenger Association statistics. Then, an average emission factor was calculated by assuming the ratio of passenger-miles on electric-powered Amtrak routes to passenger-miles on diesel-powered Amtrak routes was equivalent to the ratio between miles of electric-powered routes to the miles of diesel-powered routes. An adjustment factor was used to address longer rail distances than flight distances.

Emissions factors and data sources: Amtrak timetables for train distances;[13] Amtrak reported diesel fuel used in revenue operation;[14] Annual electricity consumption by Amtrak, passenger-miles traveled on Amtrak;[15] EPA electricity generation and emissions by state;[16] Rail ridership by state.[17]

Assumptions and limitations: This analysis only explored CO_2 emissions (no additional GHGs) and did not include travel to and from airports and train stations (i.e., "last mile" calculations). Additionally, all flights were assumed to be one-way direct flights and economy class. Road

---

[13] https://www.amtrak.com/train-schedules-timetables.

[14] https://www.amtrak.com/content/dam/projects/dotcom/english/public/documents/environmental1/Amtrak-Sustainability-Report-FY18.pdf.

[15] https://www.bts.gov/content/rail-profile.

[16] https://www.epa.gov/egrid.

[17] https://www.railpassengers.org/resources/ridership-statistics/.

travel was not included in this analysis. The scope of the report was limited to only the northeastern United States.

Source: M. Chester and A. Horvath (2010). Life-Cycle Assessment of High-Speed Rail: The Case of California. *Environmental Research Letters*

Overview: This analysis compared lifecycle emissions from air, rail, and road travel in California. For each mode of travel, emissions were calculated in CO_2 equivalents (CO_2e) from separate emissions calculations of sulfur dioxide, carbon monoxide (CO), nitrogen oxides, volatile organic compounds, and particulate matter (PM) ≤10 micrometers in diameter.

Description of model and method development: For rail emissions estimates, a California High Speed Rail (CAHSR) inventory was developed by estimating energy consumption and subsequent emissions from vehicle, infrastructure, and electricity production components. Electricity consumption was based on the German InterCity Express (ICE) HSR. Lifecycle emissions were estimated using the *SimaPro* life-cycle assessment (LCA) calculator and *Ecoinvent* database, which includes emissions from station construction, station energy usage, maintenance, and other components of the rail lifecycle. Both low and high occupancy scenarios were evaluated. Ridership numbers were based on CAHSR statistics and estimates. For aircraft emissions, small, mid-size, and large aircraft sizes were modeled. For each LCA component, environmental performance was calculated per passenger-kilometer traveled. Total emissions from all actives were calculated using an equation from Chester and Hovath 2009.[18] For road travel, emissions were estimated by evaluating vehicle, infrastructure, and fuel components. A lifecycle inventory was provided which broke down the components of rail emissions. Both low and high occupancy scenarios were evaluated.

Emissions factors and data sources: Lifecycle inventory of automobiles and aircraft;[19] *SimaPro* LCA calculator;[20] *Ecoinvent* lifecycle inventory database.[21]

Assumptions and limitations: This analysis used a consistent vehicle electricity consumption estimate of 170 kWh for rail travel, based on the electricity consumption of the German ICE HSR. The Western Electricity Coordinating Council electricity mix factors were used to calculate emissions from electricity usage.

---

[18] https://iopscience.iop.org/article/10.1088/1748-9326/4/2/024008/pdf.

[19] https://iopscience.iop.org/article/10.1088/1748-9326/4/2/024008.

[20] https://simapro.com/.

[21] https://ecoinvent.org/.

Source: S. Baumeister and A. Leung (2021). The Emissions Reduction Potential of Substituting Short-Haul Flights with Non-High-Speed Rail (NHSR): The Case of Finland. *Case Studies on Transport Policy*

Overview: This analysis evaluated CO_2e emissions for short-haul flights and non-high-speed rail in Finland. Sixteen city pairs were analyzed and emissions as well as travel time were included from door-to-door (last mile).

Description of model and method development: All trains in this study were electric, and the only emissions considered were those emitted from electricity production. The LIPASTO (Finnish acronym for Liikenteen Päästöinventaario, which translates to 'Transport Emissions Inventory' in English) unit emissions database was used to find the electricity consumption per passenger-kilometer of different train types. Calculations were made for both CO_2 and methane (CH_4) emissions from electricity production based on predetermined estimates of grams released per kWh. A real travel time was calculated by adding additional time to account for arriving at the station and finding the correct platform. CO_2e emissions were calculated based on aircraft type, route, and great circle distance to the base airport. A lengthening factor was applied for short-haul flights to account for stacking, traffic, and weather. Aircraft fuel data were extracted from the European Environment Agency Air Pollutant Emissions Inventory Guidebook, using emissions factors based on emissions per kilogram fuel burned. Separate calculations were made for CO_2, CH_4, and nitrous oxide (N_2O) emissions based on assumed values from the LIPASTO unit emissions database. Per-passenger emissions were calculated by dividing by number of seats on the plane and multiplying by the average load factor. Emissions from buses were calculated using an average vehicle mass and capacity. Car occupancy was set to an average number of passengers, and diesel car mileage was set to the country average. Distance and travel time were calculated using the Google Maps route planner, assuming the fastest and most direct routes. Emissions data were provided by the LIPASTO database. The CO_2e emissions per passenger in kilograms for all transportation modes were calculated based on the Intergovernmental Panel on Climate Change Fifth Assessment Report.

Emissions factors and data sources: LIPASTO unit emissions database for passenger and freight transport in Finland;[22] Intergovernmental Panel on Climate Change Fifth Assessment Report.[23]

Assumptions and limitations: This analysis was based on rail travel in Finland, so specific emissions factors may not be directly applicable to transportation systems in the United States. The calculations were focused on non-high-speed rail. Average load factors were used for each mode, and diesel car mileage was assumed to be the country average. There was a heavy reliance on the LIPASTO unit emissions database, which provides data specific to Finland.

---

[22] http://lipasto.vtt.fi/yksikkopaastot/index.htm.

[23] https://www.ipcc.ch/report/ar5/syr/.

Source: S. Baumeister (2019). Replacing Short-Haul Flights with Land-Based Transportation Modes to Reduce Greenhouse Gas Emissions: The Case of Finland, *Journal of Cleaner Production*

Overview: This analysis evaluated the GHG reduction potential of replacing air travel with travel by rail and road in Finland. Emissions and travel time were included for door-to-door (last mile) travel.

Description of model and method development: CO_2e emissions per passenger were calculated based on LIPASTO unit emissions database (specific to Finland). The emissions from rail were based on emissions released from electricity production. Both CO_2 and CH_4 emissions were considered. A real travel time was calculated by adding additional time to account for arriving at the station and finding the correct platform. The analysis used per passenger-kilometer CO_2e emissions values based on flight route length (classified as short or long distance). Real travel time was added for check-in. CO_2e emissions per passenger were calculated based on LIPASTO unit emissions database (specific to Finland).

Emissions factors and data sources: LIPASTO unit emissions database for passenger and freight transport in Finland;[24] Intergovernmental Panel on Climate Change Fifth Assessment Report.[25]

Assumptions and limitations: This analysis was based on rail travel in Finland, so specific emissions factors may not be equivalent to transportation systems in the United States.

Source: B.M. Graver and H.C. Frey (2016). Highway Vehicle Emissions Avoided by Diesel Passenger Rail Service Based on Real-World Data. *Urban Rail Transit*

Overview: This analysis evaluated CO_2, CO, hydrocarbons, nitrogen oxide, and PM emissions associated with passenger rail service between Raleigh and Charlotte, NC. Rail emissions were calculated directly from exhaust pipe emissions measurements and compared to road emissions estimated from the EPA's Motor Vehicle Emissions Simulator (MOVES).

Description of model and method development: Per passenger-kilometer locomotive emission factors were quantified based on measured exhaust concentrations (using a portable emissions measurement system), engine activity data, and locomotive duty cycles observed during passenger rail service. Exhaust emissions concentrations were measured from the exhaust pipe during rail service. EPA's MOVES was used to estimate fleet average emission factors from light-duty gasoline vehicles. Input data related to the distributions of vehicle type and age, fuel type, emissions inspection compliance, and meteorology were obtained from the Division of Air Quality at the North Carolina Department of Environment and Natural Resources. Data were assumed to be representative of the state average for vehicle type, vehicle age, and fuel type.

---

[24] http://lipasto.vtt.fi/yksikkopaastot/index.htm.

[25] https://www.ipcc.ch/report/ar5/syr/.

Emissions factors and data sources: tailpipe measurements; MOVES.[26]

Assumptions and limitations: This analysis did not include a calculation of emissions from air travel. State averages were used for vehicle type, age, and fuel type in road travel calculations.

Source: L. Meynerts, J. Brito, I. Ribeiro, P. Peças, S. Claus, and U. Götze (2018). Life Cycle Assessment of a Hybrid Train – Comparison of Different Propulsion Systems. *Procedia CIRP*

Overview: This analysis developed an LCA for diesel trains, hybrid trains, and hybrid trains with recharging stations. Train types were compared using vehicle kilometers traveled over a period of 15 years.

Description of model and method development: This study evaluated the lifecycle impacts of three types of rail (diesel, hybrid, and hybrid with recharging stations). Lifecycle phases included raw material extraction, production, use, and end-of-life. For operational emissions, energy consumption quantities were calculated using timetables, route profile, performance/capacity, and energy conversion efficiency. Emissions were estimated from energy quantities using *SimaPro* software and the *Ecoinvent* database. For emissions from electricity used by hybrid trains, the German electricity mix from 2014 was used (686 g CO_2e/kWh). Emissions from diesel fuel generation and combustion were estimated to be 3,120 g CO_2e/liter. The environmental impact analysis was used to measure total environmental impact for specific categories, such as climate change and ozone depletion.

Emissions factors and data sources: SimaPro LCA calculator;[27] Ecoinvent life cycle inventory database.[28]

Assumptions and limitations: This analysis only examined rail travel. Assumptions about energy consumption were based on European energy consumption factors.

Source: L. Trevisan and M. Bordignon (2020). Screening Life Cycle Assessment to Compare CO_2 and Greenhouse Gases Emissions of Air, Road, and Rail Transport: An Exploratory Study. *Procedia CIRP*

Overview: This literature review analyzed ten existing studies on GHG emissions from road, air, and trail transport, including lifecycle emissions. Studies were selected based on use of comparable vehicle types, indicators (i.e., energy consumption in megajoules and emissions in CO_2e), and units expressed in passenger-kilometers.

---

[26] MOVES and Other Mobile Source Emissions Models | US EPA.

[27] https://simapro.com/.

[28] https://ecoinvent.org/.

Description of model and method development: For each travel mode, a literature review of LCA emissions was developed. The analysis compared studies based on percent of total emissions calculated at each stage in the life cycle (operation, embedded vehicle, infrastructure, and upstream energy supply). Other factors that contribute to operational emissions were considered (e.g., type of vehicle, type of journey, gradients, and driving style) as well as demand/load factors by mode. The impact of infrastructure was also included for lifecycle analysis.

Emissions factors and data sources: Online emissions calculators: EcoPassenger, 2020;[29] Mobiltool, 2020;[30] Transport Direct, 2020.[31]

Assumptions and limitations: This analysis focused on percent of emissions associated with each component of the life cycle of the transportation mode, rather than consistencies in overall generated emissions between studies. It was found that there was a heavy reliance on "eco-calculators" between studies, which were noted to have minimal detail for load factor calculations.

Source: M. Kapetanović, N. van Oort, A. Núñez, and R. Goverde (2019). Sustainability of Railway Passenger Services: A Review of Aspects, Issues, Contributions and Challenges of Life Cycle Emissions. *RailNorrköping 2019*

Overview: This analysis evaluated the holistic impact of railway service through an LCA. All GHG emissions were considered, with a focus on CO_2 emissions. Detailed steps for a life cycle "Well to Wheel" (WTW) analysis was included.

Description of model and method development: Emissions were categorized into direct emissions (from diesel consumption) and indirect emissions (from energy carrier production, maintenance, construction, etc.). Consumption emissions from studies which used direct emissions measurements from testing engines were compared. No specific emissions factors were listed from these studies. An additional analysis compared various numerical emissions calculations. Researchers found resistance to be the main calculation component for energy consumption, representing inertial and grade resistances as well as running resistances based on train characteristics. The energy consumption needed to overcome resistance was multiplied by emissions factors to get total emissions. Three quantitative emissions models were compared: International Union of Railways Method, Rail Safety Standards and Board Method, and the Assessment and Reliability of Transport Emission Models and Inventory Systems (ARTEMIS) Rail Emissions model. The comparison included equations used for energy calculations in each method. A review of rail LCA and its challenges was also included.

---

[29] http://www.ecopassenger.org/bin/query.exe/en?L=vs_uic.

[30] https://www.mobitool.ch/.

[31] https://www.transportdirect.info/.

Emissions factors and data sources: Emissions models reviewed: International Union of Railways Method, Rail Safety Standards and Board Method, and the ARTEMIS Rail Emissions model.

Assumptions and limitations: This analysis only examined rail emissions. Note, some of the information required for the emissions models used in this analysis could be challenging to obtain for a comparable U.S.-based analysis.

Source: R. Inderbitzin (2019). Switzerland: Railway or Aviation Nation? Emission Saving Potential from Replacing Air by Train Travel between Switzerland and Europe and the Possibilities for the Swiss Government to Foster This Mode Shift. *Master Thesis Series in Environmental Studies and Sustainability Science*

Overview: This analysis examined the emission-saving potential of replacing air travel with rail travel in Switzerland and Europe.

Description of model and method development: Rail distances and travel times were calculated using the Google Distance Matrix application programming interface. Emissions were estimated using the Ecopassenger emissions calculator, which uses data from the International Union of Railways CO_2 and Energy Database. The calculator separates rail into high-speed, intercity, and regional/urban travel. Air travel calculations used data from the Swiss Federal Statistical Office for all air travel statistics from 2018. Travel time was calculated by adding time for the train/drive to the airport, waiting time at the airport, flight time, check-out time at arrival airport, and train/drive to the destination. These were calculated using Google Maps, from city center to city center. The Ecopassenger emissions calculator was used to calculate flight emissions. This calculator uses flight distances and accounts for the average fleet mix from German airports as well as aircraft types, load factor, and radiative forcing.

Emissions factors and data sources: Ecopassenger.[32]

Assumptions and limitations: This analysis did not include road travel. Emission calculations were based on European-specific consumption factors and statistics.

Source: V. Dimoula, F. Kehagia, and A. Tsakalidis (2016). A Holistic Approach for Estimating Carbon Emissions of Road and Rail Transport Systems. *Aerosol and Air Quality Research*

Overview: Analysis of emissions from construction and operation of road and rail infrastructure in Greece.

Description of model and method development: Rail analysis included construction/infrastructure (track, ballast, stations, tunnels, bridges, signaling, telecommunications, manufacturing) and use/operations for a rail system. The calculations used

---

[32] http://www.ecopassenger.org/bin/query.exe/en?L=vs_uic.

the length of the track and the materials used for the track. Infrastructure and construction analysis synthesized previous studies to calculate an average tons of CO_2e/km per year from previous research. The analysis divided the rail line into smaller sections, treated all trips as nonstop, and used a simplified fuel consumption equation for passenger trains based on the locomotive type. Gradient of the vertical alignment of the route was considered when looking at fuel consumption. An average train occupancy of 75 percent was used to estimate emissions per km. Freight trains were analyzed separately from passenger trains. Road emissions analysis included road construction, extraction of raw materials, processing/transport of materials, operation and maintenance, and disposal after use. Infrastructure and construction analysis synthesized previous studies to calculate an average tons of CO_2e/km per year. For operations, an annual traffic volume was estimated. Buses were not included in the analysis; only gasoline cars were included as they were considered at the top of consumers' preferences in Greece. Engines were placed into three displacement categories, and CO_2 emissions per category were estimated based on data from manufacturing companies. Total passenger-kilometer estimates were based on observatory records using a consistent passenger load factor of 1.67. Freight road transport was included, with fuel consumption per vehicle taken from McKinnon (2009). Vehicles were categorized as passenger transport, multi-axel vehicles, and three-axel vehicles.

Emissions factors and data sources: McKinnon (2009) road freight transport stats.[33]

Assumptions and limitations: This study focused on rail and road emissions. Emission calculations were based on consumption factors and statistics in Greece.

---

[33] https://www.semanticscholar.org/paper/Benchmarking-road-freight-transport%3A-Review-of-a-McKinnon/95fceb80f1b9c7a42ea080a47c45723449dacf47.

Appendix B.
Power Grid Assumptions

Similar to Miller (2020), this analysis assumed that the electricity used for electrified portion of the Amtrak system was generated within the states through which the electrified rails ran. Table B1 below reports data provided from the Environmental Protection Agency's (EPA) eGRID data used in this analysis – reported in megawatt-hours (MWh). These data were used to calculate the average emission factor for electricity along the electrified portion of the Amtrak rail system.

Table B1. Net electricity generation (2019) and associated CO_2 emission rate from states along Amtrak's Northeast Corridor route, from EPA's eGRID.

State	Output emission rate (kg CO_2/MWh)	Net generation (MWh)
CT	216	40,050,038
DC	362	174,080
DE	323	5,258,538
MA	351	21,513,220
MD	334	39,325,596
NJ	247	70,988,176
NY	171	131,568,023
PA	343	228,994,207
RI	387	7,624,238

Abbreviations and Acronyms

ACRONYMS	EXPLANATION
ARTEMIS	Assessment and Reliability of Transport Emission Models and Inventory Systems
BTS	Bureau of Transportation Statistics
CH_4	Methane
CO	Carbon monoxide
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalents
DOT	Department of Transportation
eGRID	Emissions & Generation Resource Integrated Database
EPA	Environmental Protection Agency
FRA	Federal Railroad Administration
GHG	Greenhouse gas
GREET	Greenhouse gases, Regulated Emissions, and Energy use in Technology
ICAO	International Civil Aviation Organization
ICE	InterCity Express
kWh	Kilowatt hour
lb	Pound
LCA	Life-cycle assessment
LIPASTO	Liikenteen Päästöinventaario (Finnish for 'Transport Emissions Inventory')
MOVES	Motor Vehicle Emissions Simulator
MWh	Megawatt hour
N_2O	Nitrous oxide
PM	Particulate matter
SOV	Single occupancy vehicle
VMT	Vehicle miles traveled
Volpe	John A. Volpe National Transportation Systems Center