CLEAN CORRIDORS PLAN

March 2024

TRIMET

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1. Background and Purpose of this Plan

The purpose of the Clean Corridors Plan is to provide information for TriMet to consider in deployment of zero-emissions buses among 80+ separate bus lines as they integrate into the TriMet fleet. TriMet currently operates a fleet of approximately 700 buses, deployed from three separate garages, and has plans that may increase the fleet to up to 1,000 buses with up to five bus garages by the year 2040. TriMet seeks to prioritize deployment of zero-emissions buses to specific bus lines according to two key criteria:

- Prioritizing service on zero-emissions buses to areas experiencing poor air quality.
- Prioritizing service on zero-emissions buses to equity communities, as defined by TriMet's Equity Index

This work builds upon TriMet's previous planning efforts including the adoption of the Non-Diesel Bus Plan[1] in September of 2018, which set forth the agency's goal to stop operating diesel buses by the year 2040. This plan is also in support of key goals set forward in the Climate Action Plan,[2] which describe TriMet's overall efforts to meet regional, state, and federal climate goals and provides agency-wide targets for greenhouse gas reductions.

This plan is guided by research completed by Portland State University (PSU)'s Sustainable Atmosphere Research Lab, which has identified the relative impact of the tailpipe emissions of TriMet buses along different bus lines. This analysis was completed using the assumption that TriMet's entire bus fleet runs on renewable diesel, which has been TriMet's practice since December 2021. More details on the differences in tailpipe emissions between standard petroleum diesel and renewable diesel can be found in Appendix C.

Ultimately, TriMet's deployment of zero-emissions buses will necessarily be constrained by operating conditions, including the availability of suitable infrastructure at each bus garage and the mileage that each individual bus serving a given route needs to travel each day. It is also important to note that TriMet's bus network is continuously evolving, and that many of the bus lines referenced in this plan are likely to change in large or small ways as the zero-emissions fleet transition progresses. However, this plan provides important policy guidance to TriMet that will help determine phasing of the zero emissions bus transition and guide the timing of bus purchases and infrastructure projects. The chapters below provide a description of regional air quality conditions, TriMet's current equity index according to the most recent available data, and the results of the PSU research on emissions and overall air quality conditions by bus line. The plan ends with a recommended list of bus lines to be prioritized for deployment of zero emissions buses.

2. Regional Air Quality

The Clean Air Act identifies six principal pollutants ("criteria pollutants") and 187 hazardous air pollutants (HAPs) that can be harmful to public health and the environment.[3] Of the six criteria pollutants covered in the National Ambient Air Quality Standards, tailpipe emissions from diesel engines such as those from TriMet's current buses include three – carbon monoxide (CO), nitrogen dioxide

[1] https://trimet.org/electricbuses/pdf/TriMet-Non-Diesel-Bus-Plan-September-2018.pdf
[2] https://trimet.org/bettertransit/pdf/TriMet-Climate-Action-Plan.pdf
[3] https://www.epa.gov/criteria-air-pollutants

(NO_2), and diesel particulate matter (DPM). Tailpipe emissions from diesel engines also emit carbon dioxide (CO_2), which is a greenhouse gas that contributes to climate change. Those four elements – CO, NO_2, DPM, and CO_2 – were studied in this plan. The general status of the Portland metropolitan region's airshed with respect to each element is as follows:

- **Carbon monoxide (CO)**. In the 1980s and 1990s, Portland was in violation of the federally-allowable threshold for CO as defined by the National Ambient Air Quality Standards. Today, however, thanks to efforts such as the Department of Environmental Quality's vehicle emissions testing program, Portland is well within acceptable limits of CO in the local airshed.
- **Nitrogen Dioxide (NO_2)**. Portland is within the federally allowable threshold for NO_2 as defined by the National Ambient Air Quality Standards. However, as described in Appendix C, some researchers have indicated that the federal thresholds do not completely capture the impacts to human health that can occur at lower concentrations.
- **Carbon Dioxide (CO_2)**. CO_2 is a naturally-occurring gas and therefore is not considered an air pollutant that is hazardous to human health. CO_2 is one of several greenhouse gases that trap heat in the atmosphere, contributing to global warming. There are no federal or state thresholds for acceptable amounts of CO_2 in the Portland metropolitan region.
- **Diesel Particulate Matter (DPM)**. The 2012 Portland Area Air Toxics Solutions study[4] identified that the entire Portland metropolitan region has a higher concentration of DPM than is safe for human health, as defined by state standards. Some areas, including downtown Portland, have a concentration that is up to 19 times higher than the state threshold. Other areas of particularly high concentration of DPM include:
  - Industrial areas north of downtown, on both sides of the Willamette River – Swan Island and along Hwy 30
  - In the Columbia Corridor, including the Portland International Airport
  - Along Highway 217 and west of Hwy 217 in Beaverton
  - I-5 between Tigard and Tualatin
  - SE McLoughlin Blvd near Sellwood and Milwaukie

  Figure 1 in Appendix C provides a map of DPM concentrations regionwide.

Section 4 provides further information on the impacts from TriMet buses with respect to those four elements and Appendix C provides substantially more detail.

3. TriMet's Equity Index

In 2014, TriMet developed an Equity Index in order to help identify and prioritize service to historically marginalized populations. TriMet's Equity Index accounts for three broad categories: Title VI Populations, Barriers to Mobility, and Access.

The *Title VI Populations* category corresponds to the demographics referenced in Title VI of the Civil Rights Act of 1964, and therefore includes three factors, as follows.

- Percent minority: Populations who identify as non-white, and/or Hispanic or Latino
- Percent low income: income at or below 150% of the federal poverty level
- Percent Limited English Proficiency.

[4] https://www.oregon.gov/deq/aq/air-toxics/Pages/PATS.aspx

The *Barriers to Mobility* category includes factors that can indicate challenges in accessing transportation via personal vehicles. This category includes the following factors:

- Percent disabled
- Percent seniors
- Percent youth
- Percent poor vehicle access.

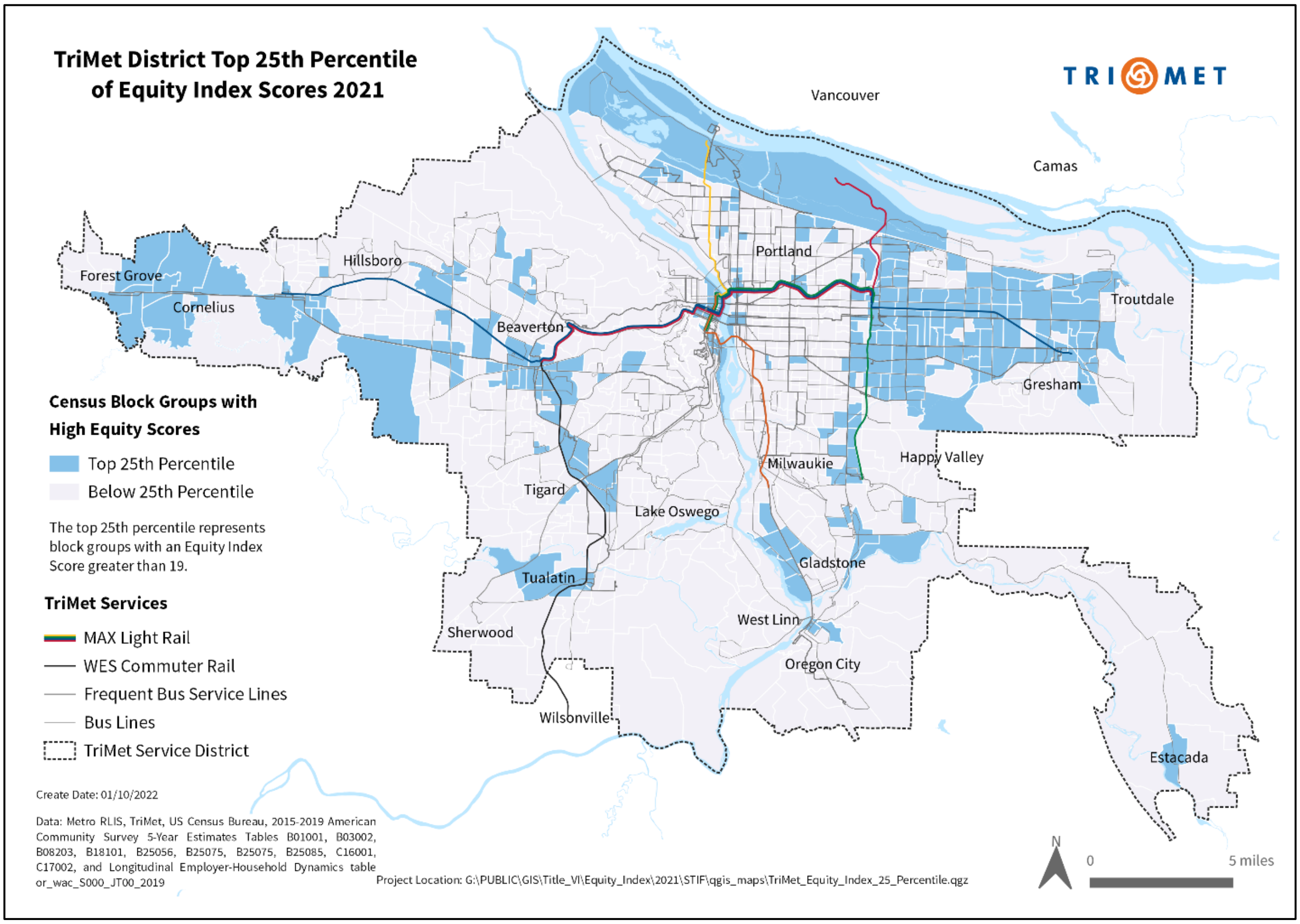
The *Access* category includes categories of destinations that are of particular importance for historically marginalized communities to be able to travel to via transit. These categories include:

- Affordable housing units
- Low and medium-wage jobs.
- Key destinations including human and social services, supermarkets/grocery stores, financial institutions, barber and beauty shops/salons, laundries and dry cleaners, hardware stores, pharmacies and drug stores, and educational institutions (high schools, middle schools, community colleges).

The equity index includes a score from 0-3 within the three categories listed above. These scores can be applied to both bus lines and census block groups. The complete score for each bus line or census block group is the summation of the scores for each of the three categories. The Equity Index incorporates data from the most recent American Community Survey, the Quarterly Census of Employment and Wages, and other sources. Appendix A provides a complete list of the data sources used in the version of the Equity Index referenced in this report.

Figure 3-1 displays the equity index by block group for the TriMet service district. In general, equity index scores are highest in East Multnomah County, parts of Forest Grove, Cornelius, Hillsboro, and Beaverton, parts of Gladstone, parts of North Portland and the Columbia Corridor, and Estacada. Scores for bus lines range from a high of 25 (for lines 9 and 20) to a low of 5 (for lines 37, 39, and 154). The full equity index scores for each bus line are listed in Appendix A.

Figure 3-1: *TriMet District Equity Area Map*



4. Air Quality Evaluation by Bus Line

PSU analyzed TriMet emissions impacts for three hazardous air pollutants – diesel particulate matter (DPM), nitrogen dioxide (NO_2), and carbon monoxide (CO), as well as one greenhouse gas, carbon dioxide (CO_2). Because of prior work PSU has completed for the Oregon Department of Environmental Quality, the analysis of DPM is more detailed than the analysis of NO_2, CO, and CO_2. PSU analyzed diesel particulate matter relative to TriMet bus routes in two ways:

- Total concentration of DPM (contributed by all sources) within 200 meters of TriMet bus routes
- Relative concentration of DPM contributed by TriMet buses, within 200 meters of TriMet bus routes

For NO_2, CO, and CO_2, PSU modeled the total concentration of each gas specifically contributed by TriMet buses within 200 meters of TriMet routes and garages.

In general, there are several key factors that affect emissions on a given bus line. These include:

- Vehicle weight (primarily determined by passenger loads)
- Vehicle speed
- Route topography and road grade
- Meteorology (specific wind and weather patterns adjacent to the route)
- Number of bus stops and amount of time spent dwelling at each

Other factors, such as engine age, also contribute to emissions. However, because TriMet does not specifically dedicate individual buses to individual bus lines, there is no way to isolate the effect of older bus engines to specific lines. PSU based all analyses on TriMet's fall 2021 route structure, bus stop locations, and schedules. Appendix B lists the estimated emissions for each bus line, and Appendix C provides the completed analysis from PSU including the methodology for calculating emissions for each specific gas. In general, the results are as follows:

- **Diesel particulate matter (DPM).** The entirety of the Portland metro region exceeds the threshold set by the state for concentrations that are safe for human health. In other words, DPM is a health hazard for everyone living in the Portland metro region, but is demonstrably worse in some areas of the region versus others. Downtown Portland, for example, displays concentrations of DPM that are 19 times higher than the recommended threshold set by the state. That said, the maximum relative contribution made by TriMet buses to the DPM concentration within 200 meters of any bus line is 2.72%, which indicates that overall, TriMet buses contribute a small portion of the DPM in a given area. In no location do TriMet buses alone raise DPM concentration levels to the state threshold.
- **Nitrogen Dioxide (**NO_2**).** TriMet bus lines vary in terms of how much NO_2 is produced per mile. Some of this is due to differences in route frequency, but other differences have to do with the factors listed in the introduction to this section – road grade, passenger load, and meteorology. In general, the Portland metropolitan area is well within national and state thresholds for concentrations of NO_2 that are acceptable for human health. As displayed on Figure 4 of Appendix C, the maximum estimated NO_2 concentration produced by TriMet buses is 6 micrograms per cubic meter, and the estimated general level of NO_2 from all sources is approximately 12.5 micrograms per cubic meter. Both of these levels are well below the National Ambient Air Quality Standard threshold of 100 micrograms per cubic meter. However, as stated in Appendix C, there is evidence that hazards to human health can occur at levels well below the federal threshold, and the modeling that PSU performed indicates that TriMet buses do likely contribute up to approximately 10% of the NO_2 within 200m of our bus lines.
- **Carbon Monoxide (CO).** The Portland metropolitan region is well within federally-allowable limits for concentrations of CO in the atmosphere. In addition, the amount of CO contributed by TriMet buses is very low. As displayed on Figure 5 of Appendix C, the estimated general level of CO in the Portland area airshed is 600 micrograms per cubic meter, which is well below the National Ambient Air Quality Standard of 10,000 micrograms per cubic meter. The maximum estimated contribution of CO by TriMet buses is 1 microgram per cubic meter within 200 meters of any bus lines.
- **Carbon Dioxide (**CO_2**).** The production of CO_2 by bus line is primarily a function of the frequency of the route. The bus line with the highest production of annual CO_2 emissions is Line 72, which also happens to have been TriMet's most frequent route in fall 2021.

Table 4-1 summarizes the top 25 bus lines according to the emissions each produces for each of the four gases analyzed. A detailed description of the emissions produced by every TriMet bus line (as of fall 2021) is provided in Appendix B. The next section describes how these outputs were weighted and combined with the equity index score described in the previous section to create a recommended prioritization.

Table 4-1: Emissions of the Top 25 Bus Lines for Each Air Pollutant/Greenhouse Gas, based on Fall 2021 Routes and Schedules

Diesel Particulate Matter			**Nitrogen Dioxide**		**Carbon Monoxide**		**Carbon Dioxide**	
Total Concentration from All Sources *(bus lines listed in descending order)*	Relative Impact of TriMet Bus Lines							
	Bus Line	% of DPM Contributed by TriMet	Bus Line	Lb/ mile/ year	Bus Line	Lb/ mile/ year	Bus Line	Metric tons/ mile/ year
75 Cesar Chavez/Lombard	9 Powell Blvd	2.72%	8 Jackson Park/NE 15th	1,947	8 Jackson Park/NE 15th	328	72 Killingsworth/82nd Ave	140
72 Killingsworth/82nd Ave	2 Division	1.85%	6 Martin Luther King Jr Blvd	1,391	72 Killingsworth/82nd Ave	215	8 Jackson Park/NE 15th	113
12 Barbur/Sandy Blvd	17 Holgate/Broadway	1.71%	12 Barbur/Sandy Blvd	1,375	12 Barbur/Sandy Blvd	228	9 Powell Blvd	112
15 Belmont/NW 23rd	6 Martin Luther King Jr Blvd	1.55%	14 Hawthorne	1,348	4 Fessenden	210	15 Belmont/NW 23rd	112
57 TV Hwy/Forest Grove	8 Jackson Park/NE 15th	1.35%	4 Fessenden	1,274	6 Martin Luther King Jr Blvd	223	2 Division	112
6 Martin Luther King Jr Blvd	33 McLoughlin/King Rd	1.26%	72 Killingsworth/82nd Ave	1,226	2 Division	235	12 Barbur/Sandy Blvd	109
9 Powell Blvd	75 Cesar Chavez/Lombard	1.19%	2 Division	1,213	14 Hawthorne	211	4 Fessenden	109
8 Jackson Park/NE 15th	73 122nd Ave	0.97%	76 Hall/Greenburg	1,205	15 Belmont/NW 23rd	168	75 Cesar Chavez/Lombard	107
2 Division	94 Pacific Hwy/Sherwood	0.95%	73 122nd Ave	1,163	73 122nd Ave	187	6 Martin Luther King Jr Blvd	104
4 Fessenden	4 Fessenden	0.93%	15 Belmont/NW 23rd	1,121	9 Powell Blvd	208	57 TV Hwy/Forest Grove	98
17 Holgate/Broadway	71 60th Ave	0.71%	9 Powell Blvd	1,116	76 Hall/Greenburg	182	20 Burnside/Stark	96
35 Macadam/Greeley	57 TV Hwy/Forest Grove	0.71%	57 TV Hwy/Forest Grove	910	75 Cesar Chavez/Lombard	121	14 Hawthorne	96
14 Hawthorne	12 Barbur/Sandy Blvd	0.69%	52 Farmington/185th	871	17 Holgate/Broadway	113	76 Hall/Greenburg	95
20 Burnside/Stark	15 Belmont/NW 23rd	0.67%	33 McLoughlin/King Rd	851	33 McLoughlin/King Rd	132	73 122nd Ave	92
71 60th Ave	62 Murray Blvd	0.65%	75 Cesar Chavez/Lombard	820	71 60th Ave	162	33 McLoughlin/King Rd	91
77 Broadway/Halsey	84 Powell Valley/Orient Dr	0.59%	71 60th Ave	759	57 TV Hwy/Forest Grove	132	17 Holgate/Broadway	79

Diesel Particulate Matter			Nitrogen Dioxide		Carbon Monoxide		Carbon Dioxide	
Total Concentration from All Sources *(bus lines listed in descending order)*	Relative Impact of TriMet Bus Lines							
	Bus Line	% of DPM Contributed by TriMet	Bus Line	Lb/ mile/ year	Bus Line	Lb/ mile/ year	Bus Line	Metric tons/ mile/ year
52 Farmington/185th	52 Farmington/185th	0.53%	17 Holgate/Broadway	757	20 Burnside/Stark	147	52 Farmington/185th	69
70 12th/NE 33rd Ave	20 Burnside/Stark	0.53%	56 Scholls Ferry Rd	660	52 Farmington/185th	93	71 60th Ave	68
33 McLoughlin/King Rd	47 Main/Evergreen	0.52%	20 Burnside/Stark	616	77 Broadway/Halsey	119	70 12th/NE 33rd Ave	65
76 Hall/Greenburg	32 Oatfield	0.52%	54 Beaverton-Hillsdale Hwy	611	70 12th/NE 33rd Ave	80	77 Broadway/Halsey	64
48 Cornell	30 Estacada	0.52%	70 12th/NE 33rd Ave	601	56 Scholls Ferry Rd	103	21 Sandy Blvd/223rd	61
62 Murray Blvd	48 Cornell	0.51%	77 Broadway/Halsey	595	54 Beaverton-Hillsdale Hwy	103	35 Macadam/Greeley	61
94 Pacific Hwy/Sherwood	78 Denney/Kerr Pkwy	0.51%	62 Murray Blvd	539	22 Parkrose	72	94 Pacific Hwy/Sherwood	50
19 Woodstock/Glisan	14 Hawthorne	0.50%	155 Sunnyside	533	74 162nd Ave	59	56 Scholls Ferry Rd	49
44 Capitol Hwy/Mocks Crest	70 12th/NE 33rd Ave	0.50%	74 162nd Ave	524	24 Fremont/NW 18th	77	54 Beaverton-Hillsdale Hwy	48

5. Bus Line Prioritization

All of the elements studied in this analysis (DPM, NO_2, CO, and CO_2) have a role in contributing to global climate change, though CO_2 contributes the most.[5] However, DPM and NO_2 also pose an additional direct risk to human health. Short-term risks from inhalation of high concentrations of DPM and NO_2 can include difficulty breathing and dizziness. Long-term risks from inhalation of high concentrations of DPM and NO_2 include a greater likelihood of respiratory diseases or cancer. It is important to note that though CO can also pose health hazards at high concentrations, there is no evidence that high concentrations of CO exist within the Portland metropolitan area, within 200 meters of bus lines or elsewhere.

Because of the risks that DPM and NO_2 directly pose to human health, this plan proposes to prioritize those two elements to develop a weighted score that ranks each bus line. The weighted score is calculated as follows:

- 50% weight for DPM levels within 200m of each bus line (contributed by all sources)
- 20% weight for the relative contribution of TriMet to DPM levels within 200m of each bus line
- 30% weight for NO_2 emissions within 200m of each bus line (contributed by TriMet)

Table 5-1 provides the weighted air quality score for the top 24 bus lines. There is a natural break in the scoring between the 24th and 25th bus line, which is why the list stops at the 24th. Appendix B includes a full list of the air quality score for all bus lines. Table 5-1 also lists the equity index score for the same lines. Of the top 24 bus lines ranked for air quality impact, 12 of them also have high equity index scores. **Bus lines that are both in the top list for air quality impacts and have a high equity score (of 18 or above) were initially recommended for prioritized deployment of zero emission buses**. However, as a response to comments received in December 2023 during the public review comment period, Line 6 Martin Luther King Jr Blvd is also included on this list despite its equity index score of 16, because of its proximity to affordable housing units.

[5] https://www.epa.gov/air-research/air-quality-and-climate-change-research

Table 5-1: *Top 24 Bus Lines Ranked by Air Quality Impact and Equity Index*

Line	**Air Quality Composite Score** **(low score = high air quality impact)**	**Equity Index Score** (high score = high equity need)	**Prioritize for ZEB deployment?**
12 Barbur/Sandy Blvd	5.0	18	✓
2 Division	7.0	22	✓
9 Powell Blvd	7.0	25	✓
4 Fessenden	8.5	19	✓
57 TV Hwy/Forest Grove	8.5	18	✓
72 Killingsworth/82nd Ave	9.0	20	✓
17 Holgate/Broadway	11.2	21	✓
71 60th Ave	14.5	18	✓
20 Burnside/Stark	16.3	25	✓
73 122nd Ave	17.3	20	✓
77 Broadway/Halsey	20.2	22	✓
35 Macadam/Greeley	21.0	18	✓
6 Martin Luther King Jr Blvd	4.4	16	✓
94 Pacific Hwy/Sherwood	22.0	14	
48 Cornell	23.0	12	
8 Jackson Park/NE 15th	5.3	16	
75 Cesar Chavez/Lombard	6.4	17	
15 Belmont/NW 23rd	7.8	17	
14 Hawthorne	12.5	15	
33 McLoughlin/King Rd	14.9	17	
52 Farmington/185th	15.8	17	
76 Hall/Greenburg	18.2	16	
70 12th/NE 33rd Ave	20.3	11	
62 Murray Blvd	20.9	8	

As shown in Table 5-1, the top bus lines recommended for priority zero emissions bus deployment are those that both score highly on the equity index *and* are among the top 24 bus lines as rated by the air quality composite score. As TriMet transitions its fleet to zero emissions buses, however, there are several practical factors that will also influence the deployment of zero emissions buses. These include:

- **Location from which the bus is deployed**. TriMet currently operates three bus garages (Merlo, Powell, and Center) and each garage supports different bus lines. TriMet's timeline for constructing the infrastructure necessary to support zero emissions buses at each garage is different. Therefore, Table 5-2 lists the top priority bus lines according to which garage from which they deploy. It is likely that Powell and Merlo garages will support additional zero emissions buses[6] sooner than Center garage because Center garage will require more extensive renovations to its maintenance building in order to support zero emissions buses.

[6] Both Powell and Merlo have some electric charging infrastructure already installed to support battery electric buses. Center has no electric charging infrastructure for battery electric buses currently.

- **Length of the schedule blocks associated with each bus line**. Battery electric buses are one type of zero emissions bus that can be limited in mileage range. TriMet's schedule blocks can range between 50 to 350 miles per day, and this varies quite a bit by bus line. Future deployment of battery electric buses on priority bus lines will be dependent on the availability of schedule blocks on that line that are short enough in mileage.

Table 5-2: *Priority Bus Lines by Bus Garage (as of Fall 2021 schedules)**

Garage	Merlo	Center	Powell
Priority Bus Lines (not necessarily in order of priority)	• Line 4 Fessenden • Line 6 MLK • Line 12 Barbur/Sandy • Line 20 Burnside/Stark • Line 35 Macadam/Greeley • Line 52 185th • Line 57 TV Highway/Forest Grove	• Line 4 Fessenden • Line 6 MLK • Line 9 Powell • Line 12 Barbur/Sandy • Line 17 Broadway/Holgate • Line 20 Burnside/Stark • Line 35 Macadam/Greeley • Line 71 60th Ave • Line 72 Killingsworth/82nd • Line 77 Broadway/Halsey	• FX 2 Division • Line 9 Powell • Line 12 Barbur/Sandy • Line 20 Burnside/Stark • Line 71 60th Ave • Line 72 Killingsworth/82nd • Line 73 122nd Ave • Line 77 Broadway/Halsey

*This listing of bus lines by garage is correct as of the fall 2021 schedule. TriMet shifts deployments of bus lines between garages, so these priorities will be re-evaluated with each new introduction of zero emissions buses to ensure the list of lines per garage is still accurate.

Appendix A: More Details on the Equity Index

The data used for developing the equity index ranking cited in this report was derived from the following sources:

Title VI Populations

- **People of Color (POC)**
  Definition: Populations who identify as non-white, and/or Hispanic or Latino.
  Data Source: American Community Survey Table B03002, 2021
- **Low-Income Population**
  Definition: Percentage households below 200% federal poverty level
  Data source: Metro definition of low-income, American Community Survey Table C17002(Ratio of Income to Poverty Level), 2021
- **Limited English Proficiency (LEP)**
  Definition: Individuals who do not speak English as their primary language and who have a limited ability to read, speak, write, or understand English can be considered LEP.
  Data Source: US Department of Justice definition of LEP, American Community Survey Table C16001, 2021

Barriers to Mobility

- **People with Disabilities**
  Definition: Percent population with a Disability
  Data Source: American Community Survey Table B18101 (Sex by Age by Disability Status), 2021
- **Senior Population**
  Definition: Percentage of population age 65 and older as defined by TriMet
  Data Source: American Community Survey Table B01001(Sex by Age), 2021
- **Youth Population**
  Definition: Populations of people ages 21 or younger
  Data Source: American Community Survey Table B01001; 2021
- **Limited Vehicle Access**
  Definition: Percent of households with zero vehicles or with 2 or more workers sharing one vehicle.
  Data Source: American Community Survey Table B08203, 2021

Access

- **Affordable Housing**
  Definition: County of rental housing w/rent less than $800 and affordable owner-occupied or available for sale valued at $175,000 or less defined by UC Davis Center for Regional Change Jobs/Housing Fit Analysis
  Data Source: American Community Survey B25056 (Contract Rent), B25061 (Rent Asked), B25075 (Value), and B25085 (Price Asked), 2021
- **Low and Medium Wage Jobs**
  Definition: County of jobs with earnings of $3,333/month or less per the UC Davis Center for Regional Change Jobs/Housing Fit Analysis and LEHD earnings definition

Data Source: Longitudinal Employer-Household Dynamics (LEHD), Origin-Destination Employment Statistics (LODES), Workplace Area Characteristics (WAC), 2021

- **Key Retail and Social Service Destinations**
Definition: Count of human and social services, key retail services, and schools as defined by the Department of Public Health
Data Source: Quarterly Census of Employment and Wages (QCEW) and Metro RLIS, 2021

Table A-1 lists the values for each bus line within each category of the equity index, as well as the total equity score.

***Table A-1**: TriMet Bus Lines by Equity Index Order (As of January 2022)*

Line	Components of the Equity Index			Total Equity Index Score
	Title VI Populations	*Barriers to Mobility*	*Access*	
Line 9-Powell Blvd	8	8	9	25
Line 20-Burnside/Stark	9	7	9	25
Line 2-Division	8	6	8	22
Line 77-Broadway/Halsey	6	7	9	22
Line 17-Holgate/Broadway	7	5	9	21
Line 74-162nd Ave	9	9	3	21
Line 19-Woodstock/Glisan	5	6	9	20
Line 72-Killingsworth/82nd Ave	8	4	8	20
Line 73-Foster/122nd Ave/Parkrose TC	9	6	5	20
Line 4-Division/Fessenden	5	5	9	19
Line 21-Sandy Blvd/223rd	8	6	5	19
Line 68-Marquam Hill/Collins Circle	7	9	3	19
Line 87-Airport Way/181st/182nd	9	8	2	19
Line 99-Macadam/McLoughlin	0	10	9	19
Line 10-Harold St	8	5	5	18
Line 12-Barbur/Sandy Blvd	3	6	9	18
Line 35-Macadam/Greeley	2	8	8	18
Line 54-Beaverton-Hillsdale Hwy	3	8	7	18
Line 57-TV Hwy/Forest Grove	9	4	5	18
Line 71-60th Ave/122nd Ave	7	5	6	18
Line 291-Orange Night Bus	4	8	6	18
Line 15-Belmont/NW 23rd	2	6	9	17
Line 22-Parkrose	6	7	4	17
Line 25-Glisan/Rockwood	9	6	2	17
Line 33-McLoughlin	2	9	6	17
Line 44-Capitol Hwy/Mocks Crest	2	6	9	17
Line 52-Farmington/185th	9	4	4	17
Line 56-Scholls Ferry Rd	2	9	6	17
Line 75-Cesar Chavez/Lombard	4	4	9	17
Line 80-Kane/Troutdale Rd	8	7	2	17

Line	Components of the Equity Index			Total Equity Index Score
	Title VI Populations	*Barriers to Mobility*	*Access*	
Line 96-Tualatin/I-5	3	7	7	17
Line 6-Martin Luther King Jr Blvd	5	5	6	16
Line 8-Jackson Park/NE 15th	4	6	6	16
Line 24-Fremont	4	5	7	16
Line 30-Estacada	2	7	7	16
Line 36-South Shore	0	8	8	16
Line 45-Garden Home	2	8	6	16
Line 55-Hamilton	1	10	5	16
Line 76-Beaverton/Tualatin	8	4	4	16
Line 78-Beaverton/Lake Oswego	6	5	5	16
Line 81-Kane/257th	8	7	1	16
Line 92-South Beaverton Express	2	7	7	16
Line 14-Hawthorne	6	4	5	15
Line 16-Front Ave/St Helens Rd	3	8	4	15
Line 23-San Rafael	8	7	0	15
Line 51-Vista	2	8	5	15
Line 88-Hart/198th	8	3	4	15
Line 1-Vermont	0	8	6	14
Line 34-River Rd	2	8	4	14
Line 79-Clackamas/Oregon City	5	9	0	14
Line 82-South Gresham	7	6	1	14
Line 94-Pacific Hwy/Sherwood	1	5	8	14
Line 11-Rivergate/Marine Dr	6	5	2	13
Line 38-Boones Ferry Rd	1	7	5	13
Line 43-Taylors Ferry Rd	0	8	5	13
Line 53-Arctic/Allen	8	5	0	13
Line 58-Canyon Rd	4	6	3	13
Line 156-Mather Rd	6	4	3	13
Line 26-Thurman/NW 18th	2	7	3	12
Line 31-Webster Rd	2	8	2	12
Line 48-Cornell	8	2	2	12
Line 84-Powell Valley/Orient Dr	6	5	1	12
Line 152-Milwaukie	4	7	1	12
Line 47-Baseline/Evergreen	6	3	2	11
Line 70-12th/NE 33rd Ave	1	2	8	11
Line 97-Tualatin-Sherwood Rd	8	3	0	11
Line 18-Hillside	0	8	2	10
Line 29-Lake/Webster Rd	2	7	1	10
Line 59-Walker/Park Way	6	3	1	10
Line 61-Marquam Hill/Beaverton	3	5	2	10
Line 155-Sunnyside	5	5	0	10
Line 46-North Hillsboro	6	3	0	9
Line 63-Washington Park	1	8	0	9

Line	**Components of the Equity Index**			**Total Equity Index Score**
	Title VI Populations	***Barriers to Mobility***	***Access***	
Line 66-Marquam Hill/Hollywood	1	3	5	9
Line 67-Bethany/158th	6	3	0	9
Line 32-Oatfield	0	6	2	8
Line 62-Murray Blvd	5	3	0	8
Line 50-Cedar Mill	3	4	0	7
Line 64-Marquam Hill/Tigard	1	4	2	7
Line 65-Marquam Hill/Barbur Blvd	0	6	1	7
Line 85-Swan Island	3	4	0	7
Line 37-Lake Grove	0	5	0	5
Line 39-Lewis & Clark	0	5	0	5
Line 154-Willamette	0	5	0	5

Appendix B: Air Quality Calculations

Table B-1: *Relative Contribution of TriMet Buses to Total DPM Emissions within 200 Meters of TriMet Bus Lines*

Line		Maximum Relative Impact (%)
9	Powell Blvd	2.72%
2	Division	1.85%
17	Holgate/Broadway	1.71%
6	Martin Luther King Jr Blvd	1.55%
8	Jackson Park/NE 15th	1.35%
33	McLoughlin/King Rd	1.26%
75	Cesar Chavez/Lombard	1.19%
73	122nd Ave	0.97%
94	Pacific Hwy/Sherwood	0.95%
4	Fessenden	0.93%
71	60th Ave	0.71%
57	TV Hwy/Forest Grove	0.71%
12	Barbur/Sandy Blvd	0.69%
15	Belmont/NW 23rd	0.67%
62	Murray Blvd	0.65%
84	Powell Valley/Orient Dr	0.59%
52	Farmington/185th	0.53%
20	Burnside/Stark	0.53%
47	Main/Evergreen	0.52%
32	Oatfield	0.52%
30	Estacada	0.52%
48	Cornell	0.51%
78	Denney/Kerr Pkwy	0.51%
14	Hawthorne	0.50%
70	12th/NE 33rd Ave	0.50%
24	Fremont/NW 18th	0.45%
96	Tualatin/I-5	0.44%
77	Broadway/Halsey	0.43%
76	Hall/Greenburg	0.42%
35	Macadam/Greeley	0.41%
72	Killingsworth/82nd Ave	0.35%
67	Bethany/158th	0.33%
155	Sunnyside	0.31%
10	Harold St	0.28%
54	Beaverton-Hillsdale Hwy	0.28%
80	Kane/Troutdale Rd	0.28%
88	Hart/198th	0.27%
21	Sandy Blvd/223rd	0.27%
74	162nd Ave	0.27%
56	Scholls Ferry Rd	0.26%
87	Airport Way/181st	0.20%

Line		Maximum Relative Impact (%)
82	South Gresham	0.19%
31	Webster Rd	0.19%
22	Parkrose	0.19%
68	Marquam Hill/Collins Circle	0.19%
19	Woodstock/Glisan	0.19%
79	Clackamas/Oregon City	0.18%
46	North Hillsboro	0.14%
156	Mather Rd	0.13%
81	Kane/257th	0.12%
36	South Shore	0.12%
61	Marquam Hill/Beaverton	0.11%
64	Marquam Hill/Tigard	0.10%
29	Lake/Webster Rd	0.10%
44	Capitol Hwy/Mocks Crest	0.09%
154	Willamette/Clackamas Heights	0.08%
23	San Rafael	0.08%
85	Swan Island	0.08%
53	Arctic/Allen	0.07%
63	Washington Park/Arlington Hts	0.07%
16	Front Ave/St Helens Rd	0.07%
92	South Beaverton Express	0.07%
1	Vermont	0.07%
65	Marquam Hill/Barbur Blvd	0.06%
11	Rivergate/Marine Dr	0.06%
58	Canyon Rd	0.06%
55	Hamilton	0.06%
66	Marquam Hill/Hollywood	0.06%
99	Macadam/McLoughlin	0.05%
50	Cedar Mill	0.05%
38	Boones Ferry Rd	0.05%
25	Glisan/Rockwood	0.05%
34	Linwood/River Rd	0.05%
45	Garden Home	0.04%
152	Milwaukie	0.04%
51	Vista	0.04%
39	Lewis & Clark	0.04%
43	Taylors Ferry Rd	0.03%
26	Thurman/NW 18th	0.03%
97	Tualatin-Sherwood Rd	0.03%
37	Lake Grove	0.02%
59	Walker/Park Way	0.01%
18	Hillside	0.01%

Table B-2: *Estimated Pounds/Mile/Year of TriMet NO_2 Emissions by Bus Line*

Line		NO_2 Emissions (lb/mile/yr)
8	Jackson Park/NE 15th	1,947
6	Martin Luther King Jr Blvd	1,391
12	Barbur/Sandy Blvd	1,375
14	Hawthorne	1,348
4	Fessenden	1,274
72	Killingsworth/82nd Ave	1,226
2	Division	1,213
76	Hall/Greenburg	1,205
73	122nd Ave	1,163
15	Belmont/NW 23rd	1,121
9	Powell Blvd	1,116
57	TV Hwy/Forest Grove	910
52	Farmington/185th	871
33	McLoughlin/King Rd	851
75	Cesar Chavez/Lombard	820
71	60th Ave	759
17	Holgate/Broadway	757
56	Scholls Ferry Rd	660
20	Burnside/Stark	616
54	Beaverton-Hillsdale Hwy	611
70	12th/NE 33rd Ave	601
77	Broadway/Halsey	595
62	Murray Blvd	539
155	Sunnyside	533
74	162nd Ave	524
21	Sandy Blvd/223rd	469
48	Cornell	461
24	Fremont/NW 18th	455
94	Pacific Hwy/Sherwood	446
35	Macadam/Greeley	438
22	Parkrose	429
78	Denney/Kerr Pkwy	421
88	Hart/198th	418
67	Bethany/158th	405
47	Main/Evergreen	353
58	Canyon Rd	346
81	Kane/257th	339
87	Airport Way/181st	336
44	Capitol Hwy/Mocks Crest	319
79	Clackamas/Oregon City	312
32	Oatfield	282
19	Woodstock/Glisan	274

Line		NO_2 Emissions (lb/mile/yr)
31	Webster Rd	268
68	Marquam Hill/Collins Circle	263
10	Harold St	244
85	Swan Island	231
152	Milwaukie	178
96	Tualatin/I-5	175
26	Thurman/NW 18th	168
16	Front Ave/St Helens Rd	166
25	Glisan/Rockwood	160
30	Estacada	156
63	Washington Park/Arlington Hts	152
80	Kane/Troutdale Rd	150
45	Garden Home	146
156	Mather Rd	119
23	San Rafael	115
39	Lewis & Clark	114
82	South Gresham	88.8
34	Linwood/River Rd	88.4
53	Arctic/Allen	88.3
61	Marquam Hill/Beaverton	82.9
66	Marquam Hill/Hollywood	81.3
154	Willamette/Clackamas Heights	73.1
64	Marquam Hill/Tigard	63.0
43	Taylors Ferry Rd	60.4
38	Boones Ferry Rd	59.8
65	Marquam Hill/Barbur Blvd	59.3
97	Tualatin-Sherwood Rd	52.1
99	Macadam/McLoughlin	51.0
11	Rivergate/Marine Dr	50.7
51	Vista	47.8
1	Vermont	45.5
46	North Hillsboro	43.7
84	Powell Valley/Orient Dr	42.5
36	South Shore	38.4
92	South Beaverton Express	36.9
29	Lake/Webster Rd	32.6
18	Hillside	20.0
59	Walker/Park Way	19.9
50	Cedar Mill	19.6
55	Hamilton	14.4
291	Orange Night Bus	10.8

Table B-3: *Estimated Pounds/Mile/Year of TriMet CO Emissions by Bus Line*

Line		**CO Emissions (lb/mile/yr)**
8	Jackson Park/NE 15th	328
72	Killingsworth/82nd Ave	215
12	Barbur/Sandy Blvd	228
4	Fessenden	210
6	Martin Luther King Jr Blvd	223
2	Division	235
14	Hawthorne	211
15	Belmont/NW 23rd	168
73	122nd Ave	187
9	Powell Blvd	208
76	Hall/Greenburg	182
75	Cesar Chavez/Lombard	121
17	Holgate/Broadway	113
33	McLoughlin/King Rd	132
71	60th Ave	162
57	TV Hwy/Forest Grove	132
20	Burnside/Stark	147
52	Farmington/185th	93
77	Broadway/Halsey	119
70	12th/NE 33rd Ave	80
56	Scholls Ferry Rd	103
54	Beaverton-Hillsdale Hwy	103
22	Parkrose	72
74	162nd Ave	59
24	Fremont/NW 18th	77
62	Murray Blvd	65
35	Macadam/Greeley	65
48	Cornell	74
21	Sandy Blvd/223rd	45
88	Hart/198th	70
78	Denney/Kerr Pkwy	79
155	Sunnyside	61
44	Capitol Hwy/Mocks Crest	61

Line		**CO Emissions (lb/mile/yr)**
19	Woodstock/Glisan	51
67	Bethany/158th	47
32	Oatfield	46
47	Main/Evergreen	43
58	Canyon Rd	46
87	Airport Way/181st	56
94	Pacific Hwy/Sherwood	36
81	Kane/257th	48
68	Marquam Hill/Collins Circle	52
31	Webster Rd	42
10	Harold St	43
79	Clackamas/Oregon City	42
26	Thurman/NW 18th	27
154	Willamette/Clackamas Heights	7.4
51	Vista	10.8
65	Marquam Hill/Barbur Blvd	8.0
38	Boones Ferry Rd	8.8
64	Marquam Hill/Tigard	6.3
1	Vermont	6.6
99	Macadam/McLoughlin	6.1
46	North Hillsboro	8.9
97	Tualatin-Sherwood Rd	7.2
11	Rivergate/Marine Dr	6.5
92	South Beaverton Express	5.3
36	South Shore	5.3
29	Lake/Webster Rd	5.4
84	Powell Valley/Orient Dr	5.3
18	Hillside	3.5
59	Walker/Park Way	3.2
50	Cedar Mill	2.9
55	Hamilton	2.2
291	Orange Night Bus	1.7
37	Lake Grove	1.0

Table B-4: *Estimated Metric Tons/Mile/Year of TriMet CO_2 Emissions by Bus Line*

Line		CO_2 Emissions (metric tons/mile/yr)
72	Killingsworth/82nd Ave	140
8	Jackson Park/NE 15th	113
9	Powell Blvd	112
15	Belmont/NW 23rd	112
2	Division	112
12	Barbur/Sandy Blvd	109
4	Fessenden	109
75	Cesar Chavez/Lombard	107
6	Martin Luther King Jr Blvd	104
57	TV Hwy/Forest Grove	98
20	Burnside/Stark	96
14	Hawthorne	96
76	Hall/Greenburg	95
73	122nd Ave	92
33	McLoughlin/King Rd	91
17	Holgate/Broadway	79
52	Farmington/185th	69
71	60th Ave	68
70	12th/NE 33rd Ave	65
77	Broadway/Halsey	64
21	Sandy Blvd/223rd	61
35	Macadam/Greeley	61
94	Pacific Hwy/Sherwood	50
56	Scholls Ferry Rd	49
54	Beaverton-Hillsdale Hwy	48
48	Cornell	48
74	162nd Ave	47
155	Sunnyside	44
62	Murray Blvd	44
78	Denney/Kerr Pkwy	41
47	Main/Evergreen	40
88	Hart/198th	40
67	Bethany/158th	39
24	Fremont/NW 18th	39
19	Woodstock/Glisan	37
22	Parkrose	36
79	Clackamas/Oregon City	33
58	Canyon Rd	33
44	Capitol Hwy/Mocks Crest	33
81	Kane/257th	32
87	Airport Way/181st	32
31	Webster Rd	31

Line		CO_2 Emissions (metric tons/mile/yr)
32	Oatfield	30
30	Estacada	27
85	Swan Island	26
96	Tualatin/I-5	23
10	Harold St	22
16	Front Ave/St Helens Rd	20
152	Milwaukie	16
26	Thurman/NW 18th	16
154	Willamette/Clackamas Heights	16
80	Kane/Troutdale Rd	14
45	Garden Home	13
25	Glisan/Rockwood	13
68	Marquam Hill/Collins Circle	13
23	San Rafael	12
63	Washington Park/Arlington Hts	11
34	Linwood/River Rd	9
39	Lewis & Clark	9.1
46	North Hillsboro	7.7
82	South Gresham	7.7
156	Mather Rd	7.7
66	Marquam Hill/Hollywood	7.4
61	Marquam Hill/Beaverton	7.3
53	Arctic/Allen	7.2
64	Marquam Hill/Tigard	7.2
11	Rivergate/Marine Dr	6.3
99	Macadam/McLoughlin	5.9
84	Powell Valley/Orient Dr	5.0
38	Boones Ferry Rd	5.0
97	Tualatin-Sherwood Rd	4.8
43	Taylors Ferry Rd	4.6
65	Marquam Hill/Barbur Blvd	4.4
36	South Shore	3.5
51	Vista	3.5
1	Vermont	3.4
29	Lake/Webster Rd	3.1
92	South Beaverton Express	3.1
59	Walker/Park Way	2.0
50	Cedar Mill	1.8
37	Lake Grove	1.2
18	Hillside	0.7
291	Orange Night Bus	0.6
55	Hamilton	0.5

Table B-5: *Composite Air Quality Score by Bus Line*

Rank	Route (Description)		Composite Air Quality Score *(lower score indicates a more polluting line)*
1	6	Martin Luther King Jr Blvd	4.4
2	12	Barbur/Sandy Blvd	5.0
3	8	Jackson Park/NE 15th	5.3
4	75	Cesar Chavez/Lombard	6.4
5	2	Division	7.0
6	9	Powell Blvd	7.0
7	15	Belmont/NW 23rd	7.8
8	4	Fessenden	8.5
9	57	TV Hwy/Forest Grove	8.5
10	72	Killingsworth/82nd Ave	9.0
11	17	Holgate/Broadway	11.2
12	14	Hawthorne	12.5
13	71	60th Ave	14.5
14	33	McLoughlin/King Rd	14.9
15	52	Farmington/185th	15.8
16	20	Burnside/Stark	16.3
17	73	122nd Ave	17.3
18	76	Hall/Greenburg	18.2
19	77	Broadway/Halsey	20.2
20	70	12th/NE 33rd Ave	20.3
21	62	Murray Blvd	20.9
22	35	Macadam/Greeley	21.0
23	94	Pacific Hwy/Sherwood	22.0
24	48	Cornell	23.0
25	24	Fremont/NW 18th	27.6
26	47	Main/Evergreen	27.8
27	54	Beaverton-Hillsdale Hwy	28.0
28	56	Scholls Ferry Rd	28.9
29	78	Denney/Kerr Pkwy	30.7
30	88	Hart/198th	31.8
31	21	Sandy Blvd/223rd	32.4
32	19	Woodstock/Glisan	33.8
33	32	Oatfield	34.3
34	44	Capitol Hwy/Mocks Crest	35.2
35	74	162nd Ave	35.3
36	30	Estacada	35.8
37	96	Tualatin/I-5	37.3
38	67	Bethany/158th	38.6
39	87	Airport Way/181st	39.1

Rank	Route (Description)		Composite Air Quality Score *(lower score indicates a more polluting line)*
40	10	Harold St	39.3
41	155	Sunnyside	41.8
42	22	Parkrose	43.6
43	79	Clackamas/Oregon City	44.9
44	58	Canyon Rd	45.0
45	31	Webster Rd	46.0
46	68	Marquam Hill/Collins Circle	47.2
47	81	Kane/257th	49.6
48	66	Marquam Hill/Hollywood	51.0
49	16	Front Ave/St Helens Rd	51.2
50	85	Swan Island	51.4
51	61	Marquam Hill/Beaverton	52.0
52	64	Marquam Hill/Tigard	52.6
53	45	Garden Home	52.8
54	99	Macadam/McLoughlin	55.3
55	82	South Gresham	58.1
56	84	Powell Valley/Orient Dr	58.7
57	34	Linwood/River Rd	59.1
58	152	Milwaukie	59.1
59	80	Kane/Troutdale Rd	59.9
60	36	South Shore	60.5
61	53	Arctic/Allen	61.1
62	46	North Hillsboro	62.3
63	92	South Beaverton Express	62.5
64	156	Mather Rd	62.6
65	38	Boones Ferry Rd	63.3
66	25	Glisan/Rockwood	63.7
67	11	Rivergate/Marine Dr	63.8
68	23	San Rafael	64.0
69	154	Willamette/Clackamas Heights	64.9
70	65	Marquam Hill/Barbur Blvd	65.7
71	43	Taylors Ferry Rd	66.9
72	63	Washington Park/Arlington Hts	67.4
73	26	Thurman/NW 18th	67.5
74	1	Vermont	68.0
75	29	Lake/Webster Rd	69.2
76	39	Lewis & Clark	70.8
77	50	Cedar Mill	75.8
78	51	Vista	75.8
79	55	Hamilton	76.5
80	97	Tualatin-Sherwood Rd	77.7

Rank	Route (Description)		Composite Air Quality Score *(lower score indicates a more polluting line)*
81	59	Walker/Park Way	80.4
82	291	Orange Night Bus	82.2
83	18	Hillside	82.3
84	37	Lake Grove	82.9

Appendix C: PSU Report

TriMet Diesel Bus Replacement Prioritization Project - Final Report (Revised)

Prepared for Kate Lyman and Natasha Muro, TriMet Planning and Policy

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PSU STAR LAB

Portland State University

Glossary

AGL	above ground level
B5	biodiesel
CARB	California Air Resources Board
CO	carbon monoxide
CO_2	carbon dioxide
CFR	Code of Federal Regulation
DEQ	Oregon Department of Environmental Quality
DPM	diesel particulate matter
GHG	greenhouse gas
HHV	high heating value
kW	kilowatt
lb	pound
m/s	meters per second
m/s^2	meters per second squared
ug/m^3	micrograms per cubic meter
MMBTU	Million British thermal units
mT	metric ton
mph	miles per hour
MOVES	Motor Vehicle Emissions Simulator
NAAQS	National Ambient Air Quality Standard
NED	National Elevation Dataset
NO_2	nitrogen dioxide
NO_X	total oxides of nitrogen
PSU	Portland State University
RHD	Renewable Hydrocarbon Diesel
σ_x	initial lateral dimension
σ_z	initial vertical dimension
SRC	Sigma Research Corporation
STP	Standard Tractive Power
TriMet	Tri-County Metropolitan Transportation District of
USEPA	Oregon United States Environmental Protection Agency
WRF	Weather Research and Forecasting

INTRODUCTION

Portland State University (PSU) was retained by Tri-County Metropolitan Transportation District of Oregon (TriMet) to assess tailpipe emissions from their existing bus fleet and provide a ranking of each route based on the adverse air quality impacts. As of 2022, all of TriMet's combustion-based bus fleet (84 bus routes and 662 buses) is fueled by Renewable Hydrocarbon Diesel (RHD). TriMet is proposing a 20-year project to electrify the majority of their existing RHD-fueled bus fleet.

The goal of the project is to help TriMet identify which buses and fleets should take priority in the transition from RHD to electrical power based on the impact of pollutant emissions with respect to human health. Carbon dioxide (CO_2) was also considered in order to evaluate climate change impact of routes. The following deliverables from and deadlines for PSU were established:

1. Modeling of impact of diesel buses on ambient diesel particulate matter levels in the Portland Metro area.
   a. Spatial map of current levels of diesel particulate matter contributed by all other sources and TriMet buses in the Metro area based on routes and frequency of trips. (August 2, 2022 -- preliminary results; August 15, 2022 final runs)
   b. Spatial map of relative impact of TriMet buses compared to all other sources along routes. (Sept 1, 2022)
   c. Impact of transition to zero emission buses on neighborhoods impacted by TriMet bus depots. Impact to be defined both as the total net reduction in particulate matter as well as the percentage reduction in particulate matter. (Sept 1, 2022)
2. Modeling of NO_2, CO and CO_{-2} emissions and dispersion within a 200m buffer of the roadway or bus depot (Oct 1,2022)
   a. Spatial map of NO_2, CO and CO_{-2} contributed by TriMet buses in the Metro area (Oct 15, 2022)
3. Analysis and ranking of level of impact by route, by concentration within a 200m buffer of the route. (Oct 30, 2022)
4. Preliminary report with maps and recommendations for TriMet review - this report (Nov 15, 2022 -- 2 week TriMet review)
5. Final report with maps and recommendations -this report finalized (Dec 20, 2022)

To accomplish these, annual emissions of four pollutants, diesel particulate matter (diesel PM or DPM), nitrogen dioxide (NO_2), carbon monoxide (CO), and carbon dioxide (CO_2), were estimated for each bus route. Additionally, dispersion modeling of diesel PM, NO_2, and CO was conducted to assess the transport of each pollutant, estimate the annual average concentration within 200 meters of each route within the larger Portland metro area, and compare the annual average concentration of each pollutant against its respective threshold. The thresholds for each pollutant are provided in Table 1.

Table 1. Applicable Air Quality Thresholds

Pollutant	Threshold	Jurisdiction	Source
DPM	0.1 (ug/m3)	State Only	OAR 340-247-8010, Table 2. Annual averaged risk-based concentration (RBC).
NO_2	100 (ug/m3)	National, State	40 CFR part 50. NAAQS annual standard.
CO	10,000 (ug/m3)	National, State	40 CFR part 50. NAAQS 8-hr standard[1].

Emissions but not concentrations of CO_2 were modeled as the impacts from this greenhouse gas (GHG) are more consequential to climate change (emission to global atmosphere) and will not adversely affect human health within the 200m buffer.

The Method section (pp 4-17) describes the dispersion modeling approach and the data used. Using the results of the dispersion modeling and emissions analysis, each bus route was given a relative ranking based on concentration or emission level compared to all other 83 routes. The Deliverables section (pp 18-33) provides the outputs of the project, as well as additional products that were developed in the course of the project and Recommendations are on page 34.

[1] There is currently no national or state annual standard for CO. The 8-hour NAAQS was used for comparison purposes.

METHODS

General Approach

Running exhaust emissions were calculated at different points along each route since the terrain and driving conditions during the course of a bus traveling across a route varied. Each bus route was divided into 100 meter long segments from the beginning to the end of each route. The same configuration was used for the return trip (i.e., from the end of the route to the start). Emissions for each 100 meter segment was estimated using data specific to that location. Emissions estimated for each segment were then summed together for the entire "out and back" to generate a total emissions rate for the route using the MOVES calculation methodology (i.e., equation 1-6, as described below). In addition, emissions from engine startup, acceleration and bus idling were also accounted for based on TriMet data. This method results in a more robust emissions profile along each route and allows for a better emissions release characterization for dispersion modeling. Once emissions for each route were calculated, this information was used in the CALPUFF (USEPA, 1995) dispersion model to estimate concentrations in the Portland region. The approach used for emissions and dispersion of the bus routes was also used for TriMet Transit Center and Bus Depots, as described in detail below.

Emissions Inventory

Emissions of diesel PM, NO_2, and CO were estimated using the emissions calculation method developed by the EPA's office of Transportation and Air Quality for use in the Motor Vehicle Emissions Simulator (MOVES) model for on-road vehicles. MOVES is a bottom up emissions model that was developed to calculate emissions from several types of on-road vehicles, such as trucks, cars, transport buses, and off-road vehicles, such as backhoes, forklifts, and front end loaders. (EPA, 2021) The MOVES model uses several user provided variables (e.g., vehicle type, fuel, emission control technology), and vehicle-specific variables (e.g., weight, speed, road grade) to estimate the expected power output (i.e., scaled tractive power [STP]) of a given vehicle at a given point in time. An emission rate for a given pollutant is then assigned based on the vehicle type, fuel type, and calculated STP. The emission rates were developed by the

EPA using laboratory test data. Lastly, location-specific variables (e.g., total number of vehicles, temporal activity rates) were used to estimate emissions of a given pollutant for the modeling domain.

Emissions of CO2 were estimated using Equation C-1 from Title 40 of the code of federal regulations, subpart C, part 98. This method uses the carbon intensity of various types of fuels and derives annual emissions based on the total amount of fuel consumed during operation. Additional information is provided in the next section.

As will be discussed below, various pieces of information were required to estimate emissions from each bus route, transit center, and bus depot. TriMet provided the majority of the key information necessary for this effort. Table 2 provides an overview of the information provided by TriMet and how it was used in the emission estimation and modeling framework.

Table 2 - Data Sources from TriMet[2]

Variable	Source	How It Was Used
Bus Routes	ArcGIS shapefile dataset provided by TriMet.	Diesel PM, NO_2, CO emissions estimates and dispersion modeling. CO emissions estimates.
Bus Stops	ArcGIS shapefile dataset provided by TriMet.	Diesel PM, NO_2, CO emissions estimates and dispersion modeling.
Bus Fleet Inventory	Microsoft Excel dataset provided by TriMet.	Diesel PM, NO_2, CO emissions estimates and dispersion modeling.
Bus Headway Data	Microsoft Excel dataset provided by TriMet.	Estimate hourly/annual bus frequencies for each route, transit center, and bus depot.
Bus Speeds along each route	Microsoft Excel dataset provided by TriMet.	Diesel PM, NO_2, CO emissions estimates and dispersion modeling.
Fuel Usage	Microsoft Excel dataset provided by TriMet.	CO_2 emissions estimates. Average fuel economy was calculated to be 5.1 mpg or 0.20 gal/mile.
Average Idling Time at bus stops/depots	TriMet Estimate.	Diesel PM, NO2, CO emissions estimates from idling.

[2] Data provided by TriMet is current as of Fall 2021.

Running Exhaust Emissions

The initial step in the MOVES emission estimation method was calculating the STP associated for each 100 meter segment along each route. STP was estimated using equation 1-6 (EPA, 2020), as shown below.

Equation 1-6:

$$STP = \frac{(Av + \ Bv2 + \ Cv3 + \ M\ x\ (a\ +\ g\ x\ sin\Theta)\ x\ v)}{Fscale}$$

Where:

A, B, C = road load coefficients

A = Tire rolling resistance (kW-s/m)

B = Mechanical rotating friction/higher order rolling losses (kW- s2/m2)

C = Aerodynamic drag (kW-s^3/m^3)

M = Weighted vehicle mass (metric tonnes)

g = acceleration due to gravity (9.81 m/s^2)

V = instantaneous vehicle speed (m/s)

A = instantaneous bus acceleration (m/s^2)

Sin Θ = road grade

Fscale = scaling factor (unitless)

Road load coefficients. Coefficients A, B, and C were estimated using a weighted average mass (see below) of the TriMet bus inventory and the equations in Table K-1 of Appendix K (EPA, 2021)

Weighted Vehicle Mass. The vehicle mass was estimated using a weighted average mass of the TriMet bus inventory. A weighted average was calculated using the estimated mass of each TriMet bus and the total quantity of each type of bus. The estimated mass assumes the average weight of an empty bus and a full load. All bus inventory mass and load data were provided by TriMet.

Instantaneous Vehicle Speed. Bus speed data along each route was provided by TriMet. The bus speed data were from Fall of 2021 and generally were available for most locations along each route.

Instantaneous Vehicle Acceleration. Vehicle acceleration was estimated using two methods depending on whether there is a bus stop within a given 100 meter segment. In instances where there were no bus stops within a given segment, acceleration was calculated using the difference in vehicle speed between the segment where the emissions are being estimated and the previous segment. In instances where there are bus stops, it would be expected that vehicle acceleration would be greater due to the bus needing to achieve cruising speed. In these instances, acceleration was estimated assuming a bus would achieve cruising speed equal to the speed of the next 100 meter segment.

Road Grade. Road grade was calculated for each 100 meter segment using National Elevation Dataset (NED) 10-meter terrain data from the US Geological Survey and ArcGIS Pro software. The percent grade was then converted to radians (theta) prior to going into the equation.

Fscale. A scaling factor of 10 was used from Table 1-3 of the EPA guidance document (EPA, 2021). This scaling factor is representative of urban buses.

Using the data provided by TriMet and Equation 1-6, the STP was then calculated for each 100 meter segment along each route. The STP was then categorized into an operating bin consistent with EPA guidance (EPA, 2020) and then assigned a subsequent emission rate. The operating bins are identified in Table 3, below.

Table 3 (Operating Mode Definitions for Running Exhaust for Heavy-Duty Vehicles) (EPA, 2020, Table 1-4)

Operating Mode	Description	STP (skW)	Vehicle Speed (mph)
0	Deceleration/ Braking	–	< 1.0
1	Idle	–	$1 \le v \le 25$
11	Coast	$STP < 0$	$1 \le v \le 25$
12	Cruise/Acceleration	$0 \le STP \le 3$	$1 \le v \le 25$

13	Cruise/Acceleration	3 ≤ STP ≤ 6	1 ≤ v ≤ 25
14	Cruise/Acceleration	6 ≤ STP ≤ 9	1 ≤ v ≤ 25
15	Cruise/Acceleration	9 ≤ STP ≤ 12	1 ≤ v ≤ 25
16	Cruise/Acceleration	STP ‹ 12	1 ≤ v ≤ 25
21	Coast	STP < 0	25 ≤ v ≤ 50
22	Cruise/Acceleration	0 ≤ STP ≤ 3	25 ≤ v ≤ 50
23	Cruise/Acceleration	3 ≤ STP ≤ 6	25 ≤ v ≤ 50
24	Cruise/Acceleration	6 ≤ STP ≤ 9	25 ≤ v ≤ 50
25	Cruise/Acceleration	9 ≤ STP ≤ 12	25 ≤ v ≤ 50
27	Cruise/Acceleration	12 ≤ STP ≤ 18	25 ≤ v ≤ 50
28	Cruise/Acceleration	18 ≤ STP ≤ 24	25 ≤ v ≤ 50
29	Cruise/Acceleration	24 ≤ STP ≤ 30	25 ≤ v ≤ 50
30	Cruise/Acceleration	STP ‹ 30	25 ≤ v ≤ 50
33	Cruise/Acceleration	STP < 6	50 ≤ v
35	Cruise/Acceleration	6 ≤ STP ≤ 12	50 ≤ v
37	Cruise/Acceleration	12 ≤ STP ≤ 18	50 ≤ v
38	Cruise/Acceleration	18 ≤ STP ≤ 24	50 ≤ v
39	Cruise/Acceleration	24 ≤ STP ≤ 30	50 ≤ v
40	Cruise/Acceleration	STP ‹ 30	50 ≤ v

Emissions rates derived by the EPA from dynamometer testing are available by regulatory class, fuel type, and operating mode. (EPA, 2020) Emission rates corresponding to diesel fueled, urban buses were extracted from the EPA MOVES database for each operating bin. It is critical to note that the EPA directory did not include emission rates specific to the RHD fuel type TriMet uses to fuel their fleet. As a result, adjustments in the emission rates were made based on research literature and are discussed in more detail, below.

The EPA emission rates represent expected emissions release in units of grams per second. The emission rate in grams per second was then multiplied by the amount of time it would take for the bus to travel across the 100 meter segment along a given route. PSU used average route travel duration data provided by TriMet and the total length of each route, as determined by ArcGIS Pro software, to calculate the expected time it would take for a bus to traverse the 100 meter segment. The travel duration was then multiplied by the emission rate to estimate emissions on a per segment basis (grams/bus-segment). This emission rate was then multiplied by the highest frequency of buses on a given route. Bus headway data were provided by TriMet and used to calculate hourly bus frequency for each route. Using these data, weighted hourly values were calculated between weekdays, Saturdays, and Sundays, and the total number of each type of day in the 2021 calendar year. As a result of this method, a separate emission rate per hour of the day for running exhaust emissions from each route were calculated and subsequently modeled. Annual emissions for each bus route were estimated by summing the hourly emissions for the 2021 calendar year.

Emissions of CO2 were estimated using Equation C-1 from Title 40 of the CFR, subpart C, part 98. Equation C-1 is presented below.

Equation C-1:

$CO_2 = 1x10^{-3}$ x F x HHV x EF

Where:

F = Mass or Volume of fuel burned

HHV = Default high heat content of fuel

EF = fuel-specific CO2 emission factor

Fuel. An average amount of fuel consumed per mile of bus travel was calculated using fuel economy data provided by TriMet.

High Heat Value (HHV). The HHV for diesel fuel from Table C-1 to 40 CFR Subpart C, Part 98 was used. <u>0.138 MMBtu/gallon fuel</u>.

Emission Factor. The emission factor for CO2 from Table C-1 to 40 CFR Subpart C, Part 98 was used. <u>73.96 kg-CO_2/MMBtu</u>.

Unlike the MOVES calculation equation method, emissions of CO_2 are a function of carbon content within the fuel and the quantity of fuel consumed. As a result, expected CO_2 emissions for each bus route will be a function of bus frequency and total length of the route.

Idling

Engine idling emissions were calculated using emission rates from Table 2-49 of the EPA guidance document (EPA, 2020). Table 2-49 emission rates were converted to grams per second and then multiplied by the expected idle time. PSU assumed an average idle time of 5 seconds at each bus stop and 65 seconds at each transit center and bus depot. Both idling times were estimated by TriMet. Using a geospatial dataset provided by TriMet, the total number of bus stops along each 100 meter segment for each route was quantified using the ArcGIS Pro software. PSU assumed that over the course of a route, a TriMet bus will stop at all bus stops along the route and would therefore, create idling emissions at that location. For transit centers, PSU used bus frequency data provided by TriMet to estimate the number of idling buses per hour at each location.

Startup

Engine startup emissions were estimated for each bus stop, transit center, and bus depot using emission factors from Table 1-5 of the EPA guidance document (EPA, 2020). As identified in Table 1-5, the emission rates change based on the expected "soak time" or time the fuel sits in the tank in a parked vehicle prior to engine start. Startup emissions from bus stops and transit centers were estimated using the lowest category of startup emissions (i.e., "a soak time of less than 6 minutes"). This is predicated on the assumption that buses at these locations will, on average, not sit for more than 6 minutes at a time. The one deviation from this assumption is for buses at bus depots. Buses at these locations sit overnight and can have soak times approaching 12 hours. As a result, startup emissions from bus depots were estimated assuming the highest category (i.e., "soak times greater than 720 minutes". Emissions from engine startup were assumed for each bus stop along each route. For the transit centers and bus depot, PSU used frequency data provided by TriMet to estimate the number of hourly engine starts for each location.

Impacts of RHD on Emissions

As previously identified, the emission rates from EPA do not currently include the impacts from RHD. As a result, PSU adjusted emission rates for each pollutant based on a review of research literature. For some pollutants (e.g., diesel PM), changes in emissions are fairly consistent across all literature. However, for some pollutants (i.e., NO_X), there is a wide range of impacts. To account for any outliers, PSU omitted the highest and lowest values and then averaged the remaining changes. A summary of the emission rate adjustments per pollutant is provided in Table 4.

Table 4 - Emission reduction using RHD fuel instead of petroleum diesel

Pollutant	Average Change	Sources
Diesel PM	-27%	Singh et. al., 2015; Na et. al, 2015; CARB 2011, McCaffery et. al, 2022; Durbin, et. al, 2021; Neste Renewable Diesel Handbook, 2020
NO_X	-2.3%	Singh et. al., 2015; Na et. al, 2015; CARB 2011, McCaffery et. al, 2022; Durbin, et. al, 2021; Ogunkoya et. al, 2015; Kousoulidou, et. al, 2014; Neste Renewable Diesel Handbook, 2020
CO	-20%	Singh et. al., 2015; Na et. al, 2015; CARB 2011; Durbin, et. al, 2021; Kousoulidou, et. al, 2014; Neste Renewable Diesel Handbook, 2020
CO_2	-2.8%	Na et. al, 2015; CARB 2011; Durbin, et. al, 2021; Kousoulidou, et. al, 2014; Neste Renewable Diesel Handbook, 2020

As shown in Table 4, impacts from the use of RHD generally reduces emissions and vary from around 2% up to 27% for NOX and diesel PM, respectively. The average change in emissions due to RHD were applied to the emissions estimates. Before transitioning to RHD, TriMet used a biodiesel blend (B5) which is 95% petroleum diesel. We expect the emissions to be somewhat lower in DPM (~10%) and somewhat higher for NOx (~5%) from using 100% petroleum diesel (Karavalakis, 2009).

Dispersion Modeling

Model Background

Air dispersion modeling was performed using the Lagrangian puff model, CALPUFF, to simulate plume release and transport from the TriMet bus fleet in the Portland metro area. CALPUFF was developed by Sigma Research Corporation (SRC) as a regulatory tool for air dispersion modeling for the California Air Resources Board (CARB). In simplest terms, a Lagrangian dispersion model takes a quantitative emission rate of a given chemical emitted from a source and tracks the plume or "puff" through time as it moves spatially through a predetermined modeling domain. The movement and transformation of the puff is driven by micro- and meso-scale meteorology, which is dictated by topography, atmospheric thermodynamics, and physical characteristics of the chemical in transport. (Scire et al., 2000) defines CALPUFF as a multi-layer, non-steady-state puff dispersion model that simulates the effects of time- and space-varying meteorological conditions on pollution transport, transformation, and removal.

The CALPUFF modeling system uses three main components to simulate the dispersion of a given pollutant and arrive at a modeled concentration: CALMET, CALPUFF, and CALPOST.

CALMET is a diagnostic meteorological model that simulates hourly meteorological conditions in a two- and three-dimensional gridded modeling domain for a user-identified time period. Temperature and wind variables are simulated in a three-dimensional gridded domain, while the other dispersion properties such as mixing layer height and surface albedo are simulated in a two-dimensional grid. The user specifies the height of the temperature and wind fields in the three-dimensional grid which are to be simulated and how many levels between the two should be included. own, completely eliminating the need for monitored data. CALMET also incorporates a geophysical processor module which uses user-input land use and terrain data to process physical surface characteristics of the modeling domain. Using the terrain and land use datasets, the geophysical processor incorporates surface elevations, land use categories, surface roughness length, albedo, Bowen ratio, soil and anthropogenic heat fluctuations, and vegetative leaf area index into the CALMET file. These variables are used by CALMET to estimate surface dispersion parameters, which are directly used in CALPUFF to simulate pollutant dispersion.

As previously identified, CALPUFF is a Lagrangian puff model that simulates the movement of a puff emitted from a source and follows it spatially and temporally through a user-identified modeling domain. The puffs are followed until they leave the modeling domain, decay into a negligible concentration, or settle onto the surface (i.e., deposition). Concentrations for a modeled pollutant are simulated at user identified points referred to as "receptors" placed within the modeling domain. Receptors are placed within the modeling domain by the user and are typically modeled at ground-level. CALPUFF simulates the transport of the puff on an hourly basis for the period of meteorology specified during the CALMET modeling phase.

CALPUFF can simulate emission releases from a wide array of source types, including point sources (e.g., exhaust stacks), volume sources (e.g., mobile sources), area sources (e.g., road dust) and line sources (e.g., roadways), among others. The user specifies release parameters, as well as the location for each source in the model. Release parameters vary by source type, but typically include the following: exhaust temperature, height above ground, release velocity, directionality of release, and emission rate. Emission rates are user input quantities that can be emitted as continuous or temporally variable rates depending on the source. Standard boundary layer conditions for CALPUFF allow the model to track up to 250,000 puffs at any one time, however, these conditions can change based on user input. The output files from the CALPUFF model include hourly concentration or deposition fluxes simulated at each receptor within the modeling domain.

CALPOST is a post-processing module and the third step in the CALPUFF modeling system. CALPOST takes the output files from CALPUFF and summarizes the results based on user specified conditions. Concentrations at each receptor can be summarized based on varying averaging periods from one-hour up to multi-year averaging periods.

Base Model Configuration

The CALPUFF model configuration used for the PSU study was used as the basis for all dispersion modeling for this project. A detailed description of each component of the CALPUFF model used for this project can be found in the Portland Air Toxics Solutions Committee Report (DEQ, 2012) and the PSU modeling report (Rogers, 2022).

The meteorological dataset prepared for the PSU study was directly used for this project without any adjustments. The meteorological dataset was prepared using 14 surface stations throughout the Portland metro area each of which are owned or operated by either the DEQ or the National Weather Service. As a result of the complex terrain in and around the Portland metro, a prognostic meteorological dataset was also included with the preparation of the meteorological dataset. In the case of the PSU study, prognostic meteorological data specifically refer to the Weather Research and Forecasting (WRF) model. The WRF model is a high resolution, 3-dimensional weather model that simulates atmospheric conditions for a predefined location and time and was prepared by Lakes Environmental Software.

Using the surface station meteorology, and prognostic data, a meteorological domain of 84 kilometers (south to north) by 81 kilometers (west to east) was processed. To account for the complex terrain and the potential micro-meteorology around the Portland metropolitan area, a grid resolution of 375-meters was simulated. Vertical meteorology was also simulated at 10 different heights ranging from ground level (0 meters) to 4 kilometers above ground level. In total, 532,224 cells, each with a volume of 0.053 cubic kilometers, for a total volume of 28,067 cubic kilometers were simulated for the entire modeling domain.

One component that changed from the original dispersion model is a reduction in the total number of modeled receptors. In the PSU study, the modeling domain encompassed an area as far south as McMinnville and as far north as Battle Ground, Washington. As the goal of this study was to assess impacts near the bus routes, receptors far outside of the greater Portland metro area and in Washington state were removed. Receptors were kept in all areas at least within 200 meters of all TriMet bus routes.

TriMet Bus Routes

As discussed above, total bus route emissions were estimated by dividing each bus route into 100-meter segments, estimating the emission rate for each segment, and then totaling on the backend. This allowed for a difference in emission rates based on operational and topographic characteristics such as road grade, bus stops, and bus speed and acceleration. This same method was used to characterize the emissions release in the CALPUFF dispersion model. Each 100 meter segment was characterized using the "volume source" source type. A volume source is defined as a virtual point located within a user-defined three-dimensional representation (i.e., "box"), which simulates the effects of emission release. A volume source is useful to model releases where there is no defined, stationary exhaust point such as moving vehicle exhaust. While there is a known exhaust point coming from the vehicle exhaust stack, the location is constantly changing due to the movement of the vehicle over a defined period.

The CALPUFF model algorithm uses several "emissions release" parameters: initial lateral dimension (σ_x), initial vertical dimension (σ_z), effective emission height, and an emission rate (constant or variable), all defined by the user, to simulate the release of a plume. (USEPA, 1995) In simple terms, the initial lateral and vertical dimensions are Gaussian dispersion coefficients used by the CALPUFF model algorithm to dictate the size of the plume and how it be released. The effective emission height is the height above ground level where a plume is expected to be released. The effective emission height is important as it allows for thermal buoyancy to be introduced due to the considerably higher temperatures existing in the exhaust stack. In total, each of these parameters are used to provide a robust plume release characterization from the exhaust stacks of the bus engines.

In the case of this project, each of these parameters were calculated using information provided by TriMet or using research literature. Table 5 identifies the release parameters used for the volume sources and the source of the data.

Table 5 - Volume Source Model Input Parameters

Parameter	Value	Source
Length of Segment	100 m	Estimated by PSU.
Release Height	3.05 m (10ft)	TriMet. Average height AGL of bus exhaust stack.

Effective Emission Height	+1.00 m (3.05 ft) 4.05 m (13.1 ft)	Release height AGL plus 1 meter to account for thermal buoyancy.
Initial Lateral Dimension (σ_x)	23.3 m	Segment length / 4.3 (EPA, 1995)
Initial vertical dimension (σ_z)	0.94 m	Effective emission height / 4.3 (EPA, 1995)
Base Elevation	Varies by segment	US Geological Survey

In total, there were 11,529 volume sources used in the CALPUFF model to characterize emissions for all 84 bus routes. The number of volume sources per route was dictated by the total length of the route (including both "to" and "from" direction), with the shortest route (Route 53, Arctic/Allen) containing 59 volume sources, and the longest route (Route 30, Estacada) containing 613 volume sources.

TriMet Transit Centers and Bus Depots

Emissions released from buses at transit centers and bus depots were characterized differently within the CALPUFF model. Although the mechanism is the same for an instantaneous plume release (i.e., exhaust stack), over the course of a calendar year, the lack of binary directionality of bus movement at these locations makes using the volume source unfeasible. For example, buses can, generally, only travel to and from while operating on a given route. In the case of bus depots and most transit centers, there are more areas the bus could travel. This is especially evident at parking lots at the bus depots and varying offloading ports at some transit centers.

In order to account for this variation, both the transit centers and bus depots were modeled as "area sources". Similar to a volume source, an area source is used to represent fugitive emissions within the CALPUFF model. One of the fundamental differences between the two, is that an area source is represented in the CALPUFF model in a two-dimensional plane as opposed to a three-dimensional plane in a volume source. The two dimensional source is represented in the model as a rectangular shape with a user defined x and y lengths. The user also includes the height of the area source and the emission rate. One of the other main differences between a volume source and an area source is that the area source model is based on a numerical integration of an emission rate over the user-defined area, while the volume source assumes the plume release occurs at a virtually derived point. (USEPA, 1995) An example useful scenario for the use of an area source is modeling exhaust from a lawn mower in a backyard over the course of a year. The height and area where the engine exhaust will be emitted (i.e., area of the backyard) is known, however, over the course of a year, the instantaneous release point of the lawn mower engine exhaust could be at any location in the area of the lawn.

To incorporate the transit centers and bus depots into the model as area sources, the shape of each location (18 transit centers and 3 bus depots) was traced via Google Earth and transposed into the CALPUFF model. Generally, the full footprint of each transit center and bus depot was included as it was assumed a bus could travel anywhere a roadway or parking lot was. However, the footprint of each location was individually assessed for potential for bus access. In instances where there were locations that could not accommodate a bus (e.g., office building), this location was not included.

In addition to the geometry of each transit center and bus depot, several other release parameters were included to better estimate plume release from these locations. The release parameters for the transit centers and bus depots for this project are identified in Table 6.

Table 6 - Area Source Model Input Parameters

Parameter	Value	Source
Source Footprint	Varies by location	Google Earth
Release Height	3.05 m (10ft)	TriMet. Average height AGL of bus exhaust stack.
Effective Emission Height	+1.00 m (3.05 ft) 4.05 m (13.1 ft)	Release height AGL plus 1 meter to account for thermal buoyancy.
Initial Vertical Dimension (σ_z)	0.94 m	Effective emission height / 4.3 (EPA, 1995)
Base Elevation	Varies by segment	US Geological Survey

DELIVERABLES

Deliverable 1. Modeling of impact of diesel buses on ambient diesel particulate matter levels in the Portland Metro area.

1a. Spatial map of current levels of diesel particulate matter contributed by all other sources and TriMet buses in the Metro area based on routes and frequency of trips.

Figure 1 below shows the modeled diesel particulate matter concentrations from all sources, including TriMet buses.

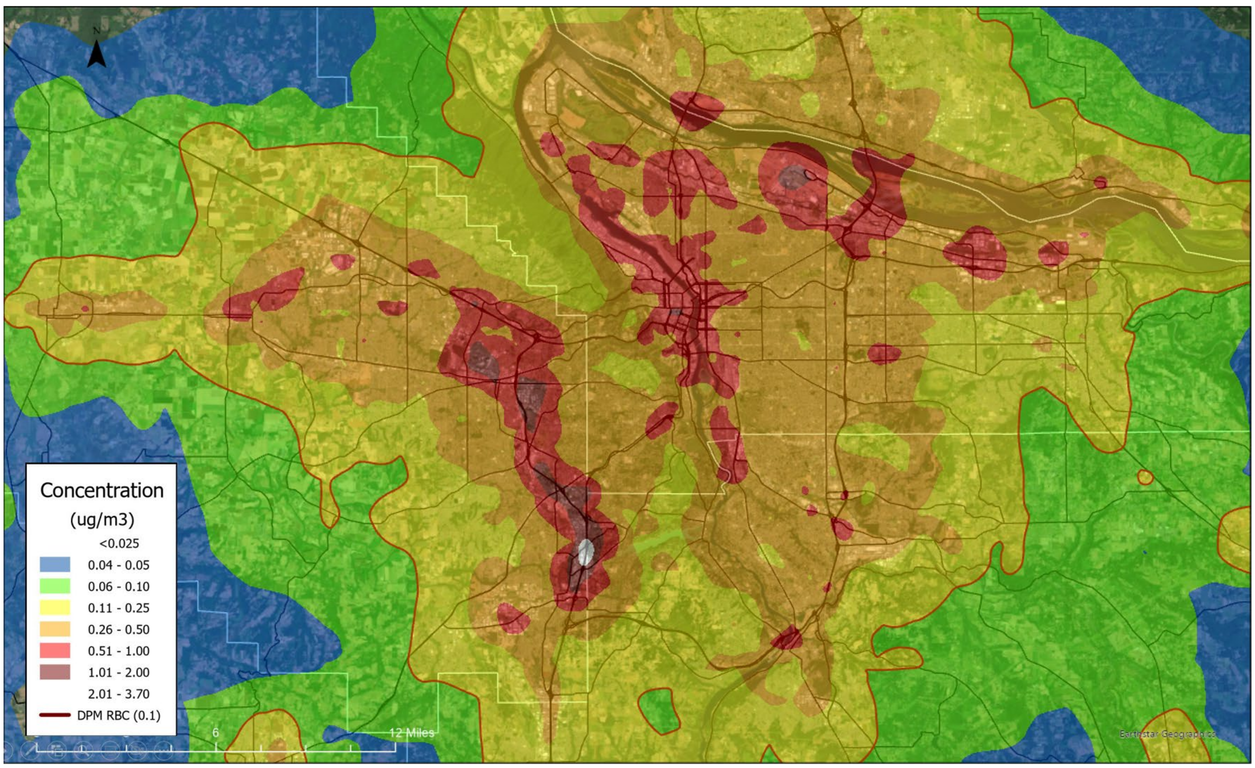

Figure 1. PSU-2020 model of all sources of diesel particulate matter based on Rogers, 2022 modified with up-to-date TriMet bus data provided by TriMet (Table 1).

Note that virtually all areas within the Portland metropolitan area are above the 0.1 ug/m3 risk-based concentration standard established by the Oregon Department of Environmental Quality and the Oregon Health Authority.

1b. Spatial map of relative impact of TriMet buses compared to all other sources along routes.

Figure 2 shows the modeled annual average concentration of DPM within 200m of the bus routes across the Portland Metro region and Figure 3 shows the impact relative to other sources of DPM in the Portland Metro region. For these maps, when routes overlap the concentrations from each bus routes are added together. This is important for assessing cumulative impact.

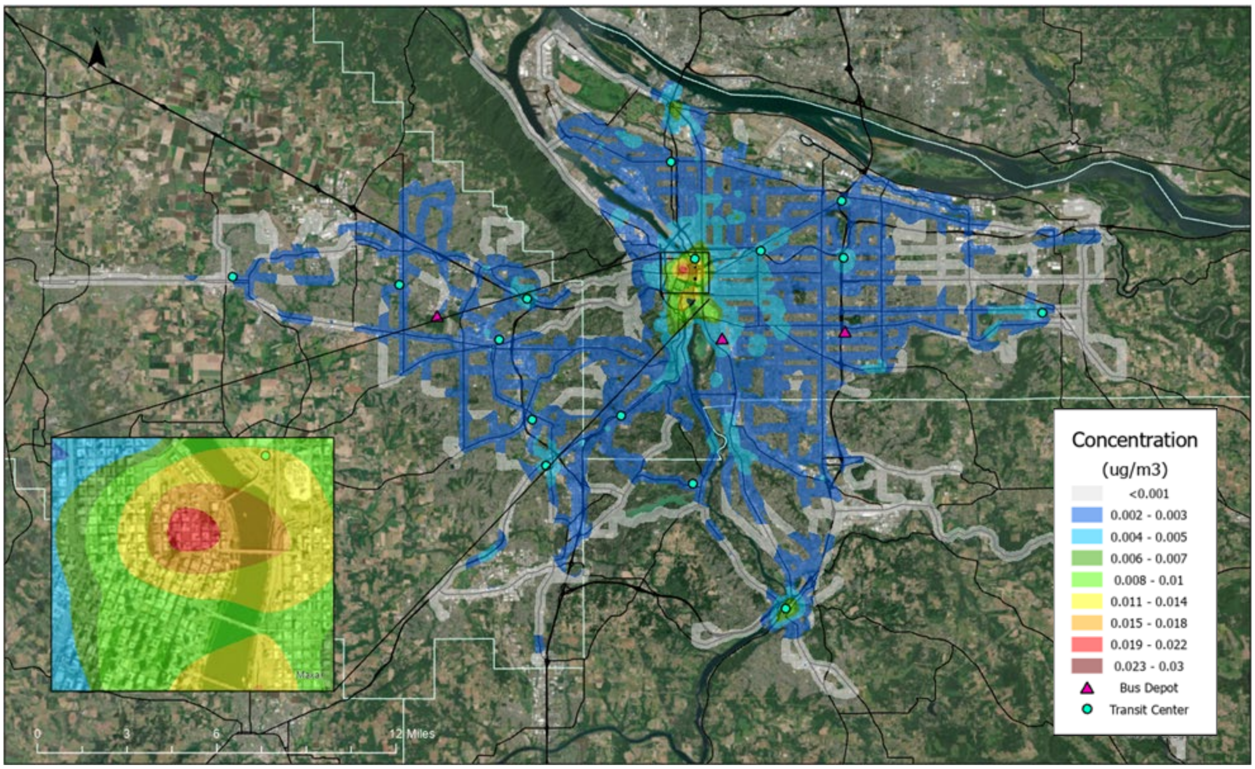

Figure 2. DPM concentrations within 200m of routes/depot/transit centers. Inset of downtown Portland.

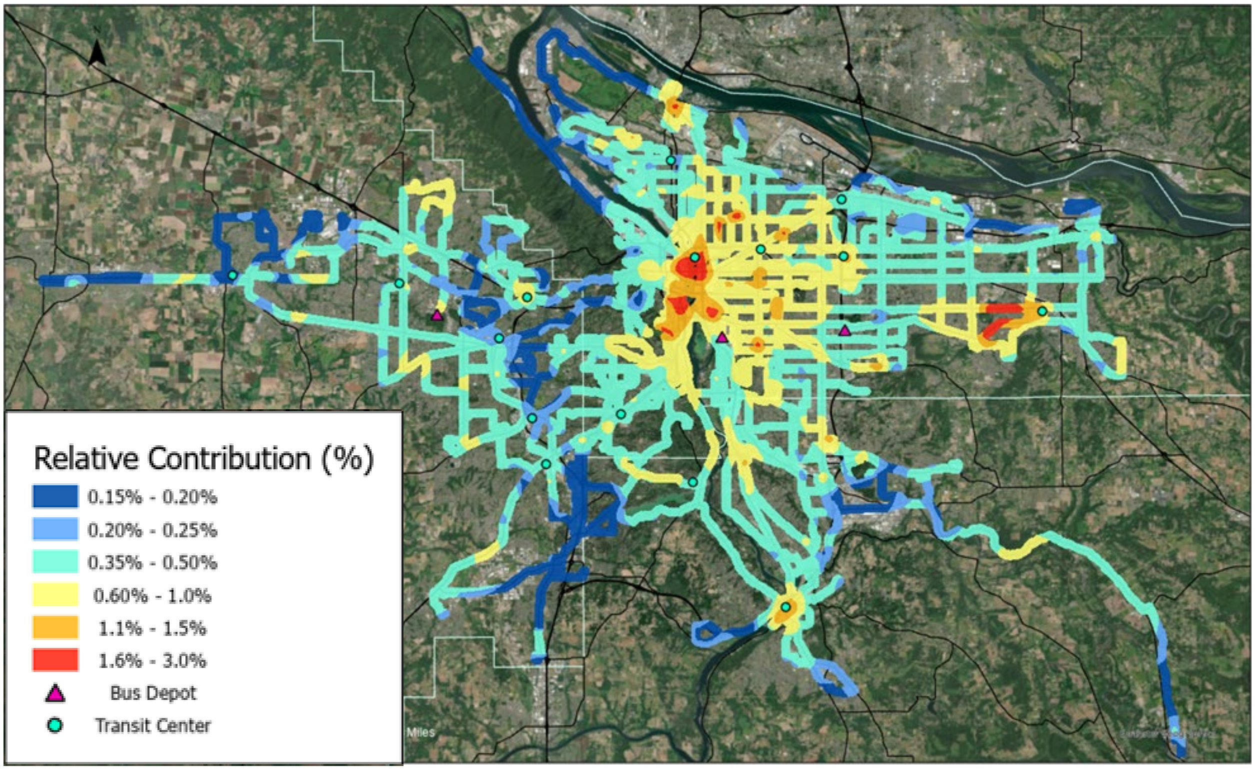

Figure 3. Relative contribution of DPM from TriMet Buses compared to all other sources of DPM.

The maps of DPM show the influence of the TriMet bus routes on pollution levels. Since many routes pass through downtown Portland, this area is disproportionately impacted and has higher DPM levels. However, there is no area in the region that exceeds the Oregon Department of Environmental Quality health-risk based standard for diesel particulate matter of 0.1 ug/m^3 on an annualized basis of TriMet bus emissions alone. The relative impact of TriMet bus DPM in the region (Figure 3) has several hotspots, in addition to the downtown area. The areas of higher impact in this analysis is due to relatively lower background levels of DPM from other sources. For instance, in the Gresham area, the hotspot is due to TriMet bus emissions in an area of relatively low DPM background concentrations so the impact of the bus is higher than it would be in an area of higher background levels. Other notable hotspots include the northwest Oregon City area, the southeast Portland area near Hosford-Abernethy, and the Northeast Portland area near Alameda.

c. Impact of transition to zero emission buses on neighborhoods impacted by TriMet bus depots. Impact to be defined both as the total net reduction in particulate matter as well as the percentage reduction in particulate matter.

The impact of zero emission buses within neighborhoods for diesel PM can be evaluated from Figure 3. The reduction would be equivalent to enhancement currently modeled to exist but in the opposite direction. For instance, for routes with a 0.6-1% enhancement currently, the conversion to zero emission buses would reduce impact by 0.6-1% on an annual basis.

2.Modeling of NO_2, CO and CO_{-2} emissions and dispersion within a 200m buffer of the roadway or bus depot.

a. Spatial map of NO_2, CO and CO_{-2} contributed by TriMet buses in the Metro area.

Below Figure 4 and 5, show the modeled concentrations of NO_2 and CO within 200m of the bus routes in the region. Since there are no models of NO_2 and CO concentrations for the region at this spatial resolution, we are not able to assess the relative contribution of TriMet buses along their routes. However, we can compare the concentrations produced by buses to the annual background levels measured by the Oregon DEQ "urban background" station at SE Lafayette (SEL). For 2021, the urban backgrounds for NO_2 and CO were 12.5.ug/m^3 and 660 ug/m^3, respectively.

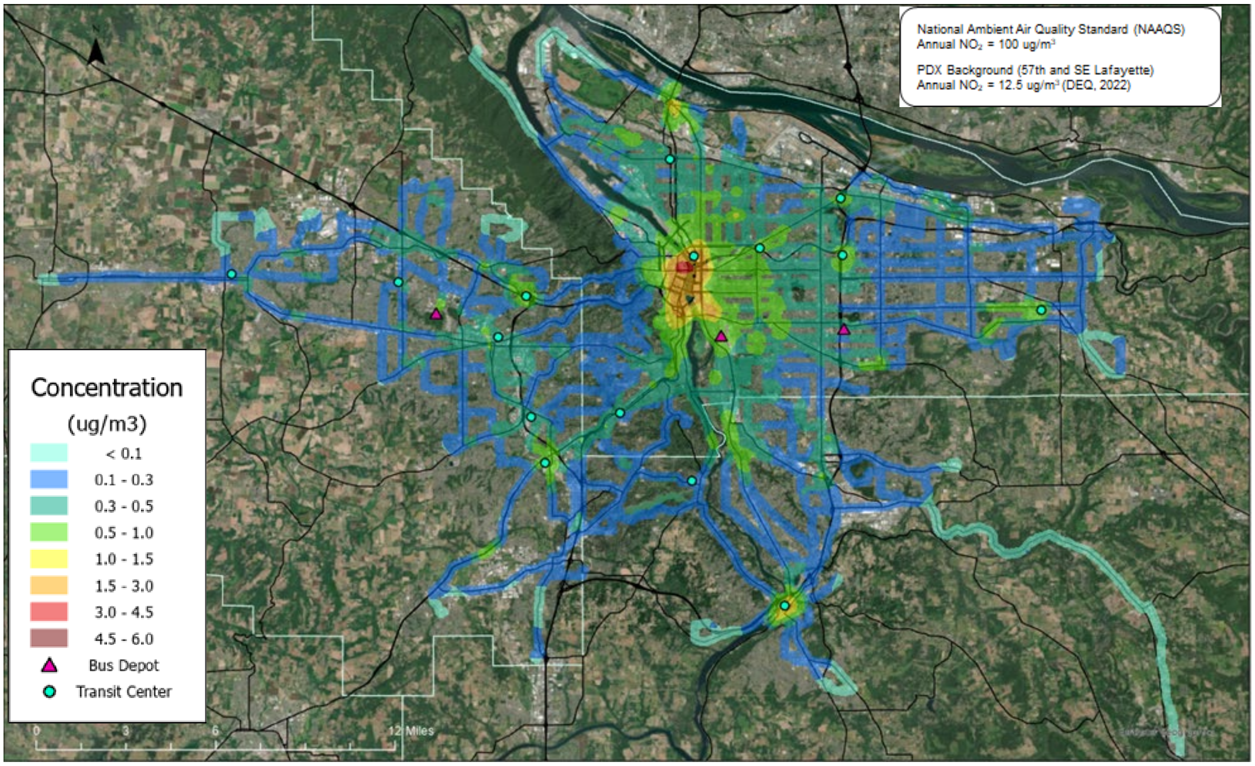

Figure 4. NO_2 concentrations within 200m of routes/depot/transit centers.

While the levels of NO_2 produced by buses are well below the National Ambient Air Quality Standards, buses appear to be significant contributors to ambient NO_2 levels particularly in the downtown and inner eastside Portland areas. While the concentrations are low relative to the standard, many epidemiological studies have documented the adverse health impact of low levels of nitrogen dioxide well below the EPA standard (Health Effects Institute, 2022). As a result, modeled concentrations of NO_2 are likely the second in hierarchy with respect to human health impacts in the Portland metro aside from diesel PM.

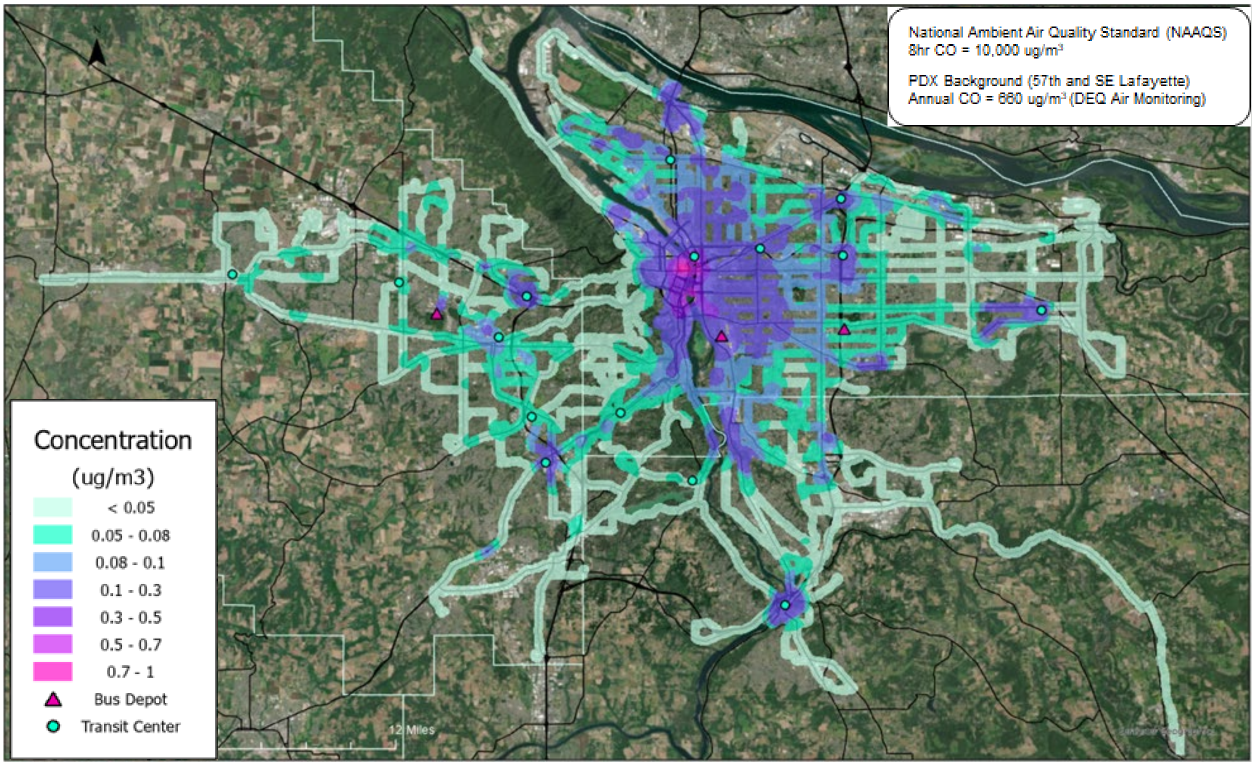

Figure 5. CO concentrations within 200m of routes/depot/transit centers.

The carbon monoxide levels produced by TriMet buses is very low. The Portland region is far from exceedance of NAAQS for CO. In addition, there are no studies that we can find that suggest that CO, at these levels, produce adverse health outcomes.

Carbon Dioxide (CO_2)

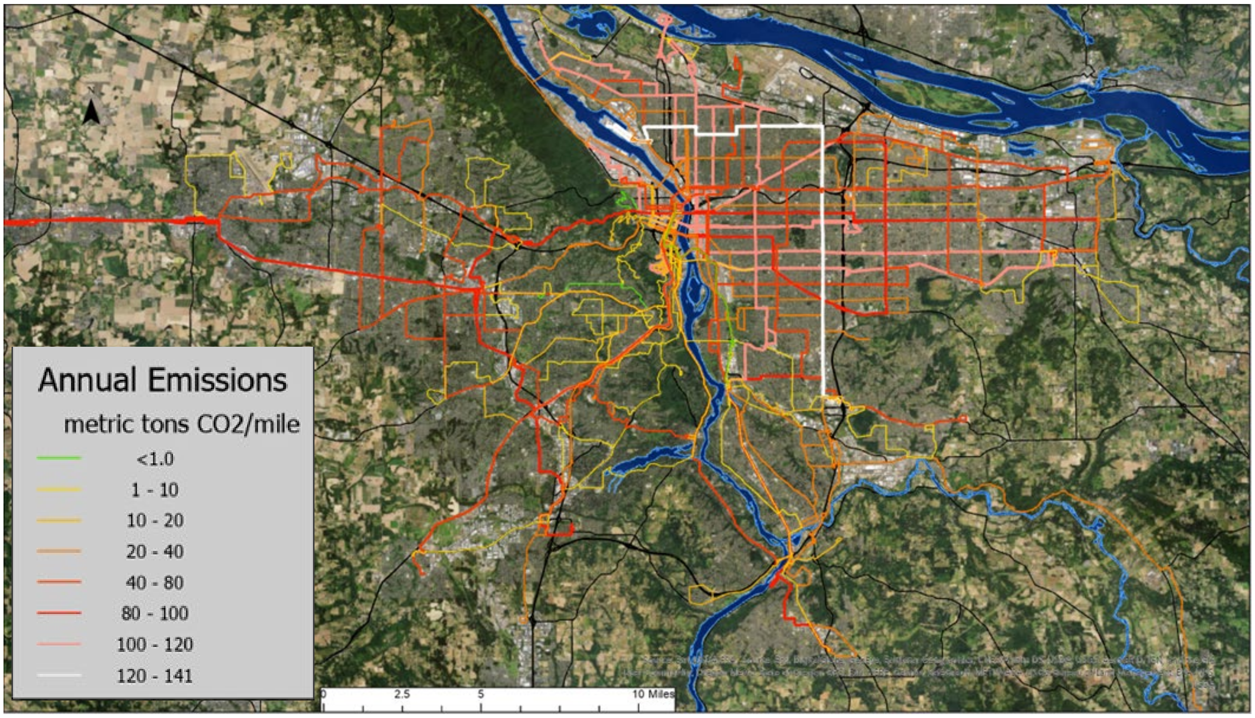

Figure 6. CO_2 emissions by mile for TriMet Buses.

The total annual emissions of CO_2 from the TriMet fleet based on Fall 2021 operating data using RHD fuel is 89,559 metric tons/year. The routes that produce the most CO_2 emissions are listed in Table 10 below. The total emission from TriMet buses can be compared to 2,500,00 metric tons of CO_2e emissions from the transportation sector in all of Multnomah County (City of Portland, 2022).

3. Analysis and ranking of level of impact by route, by concentration within a 200m buffer of the route.

Tables 7 and 8 rank the top 25 bus routes by annual emission of DPM and relative impact of Bus DPM compared to all other sources (as modeled in Rogers, 2022), respectively.

Table 7. Routes ranked by highest annual DPM emissions (mile-route) (lb/mile/yr)

Rank	Route (Description)		Annual Emissions
1	8	Jackson Park/NE 15th	7.46
2	12	Barbur/Sandy Blvd	5.84
3	6	Martin Luther King Jr Blvd	5.47
4	76	Hall/Greenburg	4.70
5	14	Hawthorne	4.63
6	4	Fessenden	4.39
7	72	Killingsworth/82nd Ave	4.39
8	15	Belmont/NW 23rd	4.38
9	2	Division	4.30
10	73	122nd Ave	4.14
11	9	Powell Blvd	3.95
12	52	Farmington/185th	3.47
13	57	TV Hwy/Forest Grove	3.25
14	75	Cesar Chavez/Lombard	3.23
15	33	McLoughlin/King Rd	3.19
16	56	Scholls Ferry Rd	2.85
17	71	60th Ave	2.71
18	17	Holgate/Broadway	2.69
19	54	Beaverton-Hillsdale Hwy	2.64
20	70	12th/NE 33rd Ave	2.34
21	20	Burnside/Stark	2.31
22	155	Sunnyside	2.28
23	77	Broadway/Halsey	2.24
24	62	Murray Blvd	2.20
25	74	162nd Ave	1.91

Table 8. Routes ranked by contribution to DPM concentration relative to all other DPM sources (based on Rogers, 2022)

By Highest Relative Impact (All Sources)			
Rank	**Route (Description)**		**Average Relative Impact (%)**
1	9	Powell Blvd	2.72%
2	2	Division	1.85%
3	17	Holgate/Broadway	1.71%
4	6	Martin Luther King Jr Blvd	1.55%
5	8	Jackson Park/NE 15th	1.35%
6	33	McLoughlin/King Rd	1.26%
7	75	Cesar Chavez/Lombard	1.18%
8	73	122nd Ave	0.97%
9	94	Pacific Hwy/Sherwood	0.95%
10	4	Fessenden	0.93%
11	71	60th Ave	0.71%
12	57	TV Hwy/Forest Grove	0.71%
13	12	Barbur/Sandy Blvd	0.69%
14	15	Belmont/NW 23rd	0.67%
15	62	Murray Blvd	0.65%
16	84	Powell Valley/Orient Dr	0.59%
17	52	Farmington/185th	0.53%
18	20	Burnside/Stark	0.53%
19	47	Main/Evergreen	0.52%
20	32	Oatfield	0.52%
21	30	Estacada	0.52%
22	48	Cornell	0.51%
23	78	Denney/Kerr Pkwy	0.51%
24	14	Hawthorne	0.50%
25	70	12th/NE 33rd Ave	0.50%

While the ranking provides information about the contribution from individual routes, spatial maps of the emission impact is important to consider.

Nitrogen dioxide (NO2) and Carbon Monoxide (CO)

Nitrogen dioxide and carbon monoxide are both EPA criteria pollutants and their ambient levels must conform to the EPA National Ambient Air Quality Standards (NAAQS). The Portland Air Quality Management Area has not been in exceedance of the EPA standards for these pollutants in over 20 years. However, these pollutants add to the overall air pollution burden for the region and contribute to the formation of ozone and secondary fine particulate matter. Table 9 ranks the top 25 bus routes by annual emission of NO2 and CO.

Table 9. Routes ranked by highest annual NO_2 and CO emissions (mile-route) (lb/mile/yr)

Rank	NO_2			CO		
	Route (Description)		Annual Emissions	Route (Description)		Annual Emissions
1	8	Jackson Park/NE 15th	1,947	8	Jackson Park/NE 15th	328
2	6	Martin Luther King Jr Blvd	1,391	72	Killingsworth/82nd Ave	215
3	12	Barbur/Sandy Blvd	1,375	12	Barbur/Sandy Blvd	228
4	14	Hawthorne	1,348	4	Fessenden	210
5	4	Fessenden	1,274	6	Martin Luther King Jr Blvd	223
6	72	Killingsworth/82nd Ave	1,226	2	Division	235
7	2	Division	1,213	14	Hawthorne	211
8	76	Hall/Greenburg	1,205	15	Belmont/NW 23rd	168
9	73	122nd Ave	1,163	73	122nd Ave	187
10	15	Belmont/NW 23rd	1,121	9	Powell Blvd	208
11	9	Powell Blvd	1,116	76	Hall/Greenburg	182
12	57	TV Hwy/Forest Grove	910	75	Cesar Chavez/Lombard	121
13	52	Farmington/185th	871	17	Holgate/Broadway	113
14	33	McLoughlin/King Rd	851	33	McLoughlin/King Rd	132
15	75	Cesar Chavez/Lombard	820	71	60th Ave	162
16	71	60th Ave	759	57	TV Hwy/Forest Grove	132
17	17	Holgate/Broadway	757	20	Burnside/Stark	147
18	56	Scholls Ferry Rd	660	52	Farmington/185th	93
19	20	Burnside/Stark	616	77	Broadway/Halsey	119
20	54	Beaverton-Hillsdale Hwy	611	70	12th/NE 33rd Ave	80
21	70	12th/NE 33rd Ave	601	56	Scholls Ferry Rd	103
22	77	Broadway/Halsey	595	54	Beaverton-Hillsdale Hwy	103
23	62	Murray Blvd	539	22	Parkrose	72
24	155	Sunnyside	533	74	162nd Ave	59
25	74	162nd Ave	524	24	Fremont/NW 18th	77

Table 10 ranks the top 25 bus routes by annual emission of CO_2 based on fixed fuel consumption. In contrast, to the calculations for DPM, NO_2 and CO, we did not take into account road grade, speed and acceleration for the emissions since this information was not available in the MOVES model for CO_2. It is unlikely that these parameters would significantly alter the rankings since the main source of CO_2 is the combustion process itself producing CO_2 and water. Carbon dioxide emissions below are a function of bus frequency on the route.

Table 10. Routes ranked by highest annual CO_2 emissions (mile-route) (metric-ton/mile/yr)

Rank	CO2 by Highest Annual Emissions (mile-route) (mT/mile/yr)		
	Route (Description)		Annual Emissions
1	72	Killingsworth/82nd Ave	140
2	8	Jackson Park/NE 15th	113
3	9	Powell Blvd	112
4	15	Belmont/NW 23rd	112
5	2	Division	112
6	12	Barbur/Sandy Blvd	109
7	4	Fessenden	109
8	75	Cesar Chavez/Lombard	107
9	6	Martin Luther King Jr Blvd	104
10	57	TV Hwy/Forest Grove	98
11	20	Burnside/Stark	96
12	14	Hawthorne	96
13	76	Hall/Greenburg	95
14	73	122nd Ave	92
15	33	McLoughlin/King Rd	91
16	17	Holgate/Broadway	79
17	52	Farmington/185th	69
18	71	60th Ave	68
19	70	12th/NE 33rd Ave	65
20	77	Broadway/Halsey	64
21	21	Sandy Blvd/223rd	61
22	35	Macadam/Greeley	61
23	94	Pacific Hwy/Sherwood	50
24	56	Scholls Ferry Rd	49
25	54	Beaverton-Hillsdale Hwy	48

Additional products generated from this work

Composite Score- TriMet Bus Route Emission Ranking Tool

Each of the modeled pollutant emissions from TriMet buses has a human health and/or environmental impact. The relative risk impact of each pollutant will depend on the health or environmental risk being evaluated.

In order to facilitate assessment of multiple risks, a "TriMet Bus Route Emission Ranking Tool" (Excel spreadsheet - TMRE-Rank.xlsx) has been prepared that has a user input functionality that allows TriMet to calculate composite rankings using their own weighting scheme. In addition to user-input, this spreadsheet also includes three suggested weight schemes for different risk foci based on our judgment and are shown and explained in Table 11, below.

Table 11. PSU Suggested Weights* (%)

Risk Focus	Weight DPM levels ranking (%)	Weight relative DPM impact ranking (%)	Weight of NO_2 emissions ranking (%)	Weight of CO emissions ranking (%)	Weight of CO_2 emissions ranking (%)
Human health	50	20	30	0	0
Regional Climate Impact	20	10	15	10	45
Global Climate Impact	5	0	5	5	85

*Rationale behind PSU suggested weights:
Human Health - the emission of DPM from buses is significant and contributes to the elevated levels experienced by the region. DPM is a known carcinogen, so DPM levels are important to consider. Relative impact of DPM acknowledges areas where buses are contributing a higher proportion in cleaner areas. Nitrogen dioxide has significant adverse health impacts even at low levels. Carbon monoxide and carbon monoxide at the levels produced are not a significant health hazard.
Regional Climate Impact - DPM is primarily composed of black carbon soot which is a climate forcer. Nitrogen dioxide and carbon monoxide are involved in ozone formation. Ozone is a climate forcer. Carbon dioxide is an important climate forcer but the contribution from buses to the background level will be small but it adds to the overall anthropogenic greenhouse gas budget of the region.
Global Climate Impact - Black carbon for the region is largely deposited out of the atmosphere as it leaves the region, however some fraction of it passes into larger circulation patterns and can be a direct climate forcer and as deposited on glaciated peaks can accelerate snow/ice melt. NO_2 and CO contribute to ozone

and secondary fine particulate matter which are climate forcers. CO_2 is an important climate forcer bus emissions add to the overall anthropogenic greenhouse gas budget of the region.

Example calculation for composite score: Route 1 "Vermont" "Human Health" Focus

Rank DPM Level = 67 (of 84)
Rank Relative DPM Impact = 63 (of 84)
Rank NO2 Emissions = 73 (of 84)
Rank CO Emissions = 70 (of 84)
Rank CO2 Emissions = 76 (of 84)

Composite Ranking = (Rank DPM level x weight %) + (Rank DPM Relative Impact x weight %) + (Rank NO2 Emissions x weight %) + (Rank CO Emissions x weight %) + (Rank CO_2 Emissions x weight %)

Composite Ranking = (67 x 50%) + (63 x 20%) + (73 x 30%) + (70 x 0%) + (76 x 0%) = 68.0

The composite score identifies the relative ranking of the route with respect to the others assessed in this study. The lower the score, the higher the impact. e.g., 1 = highest impact, 84 = lowest impact. Therefore, with a composite score of 68 out of 84, route 1 “Vermont” has a relatively lesser impact with respect to the human health focus.

Comparison of DPM from TriMet buses with Petro Diesel and R99 (current fuel)

To evaluate the impact of TriMet's decision to change fuel from petroleum diesel to R99, we modeled the concentration with both fuel sources. The reduction in DPM with R99 is particularly pronounced in the downtown area.

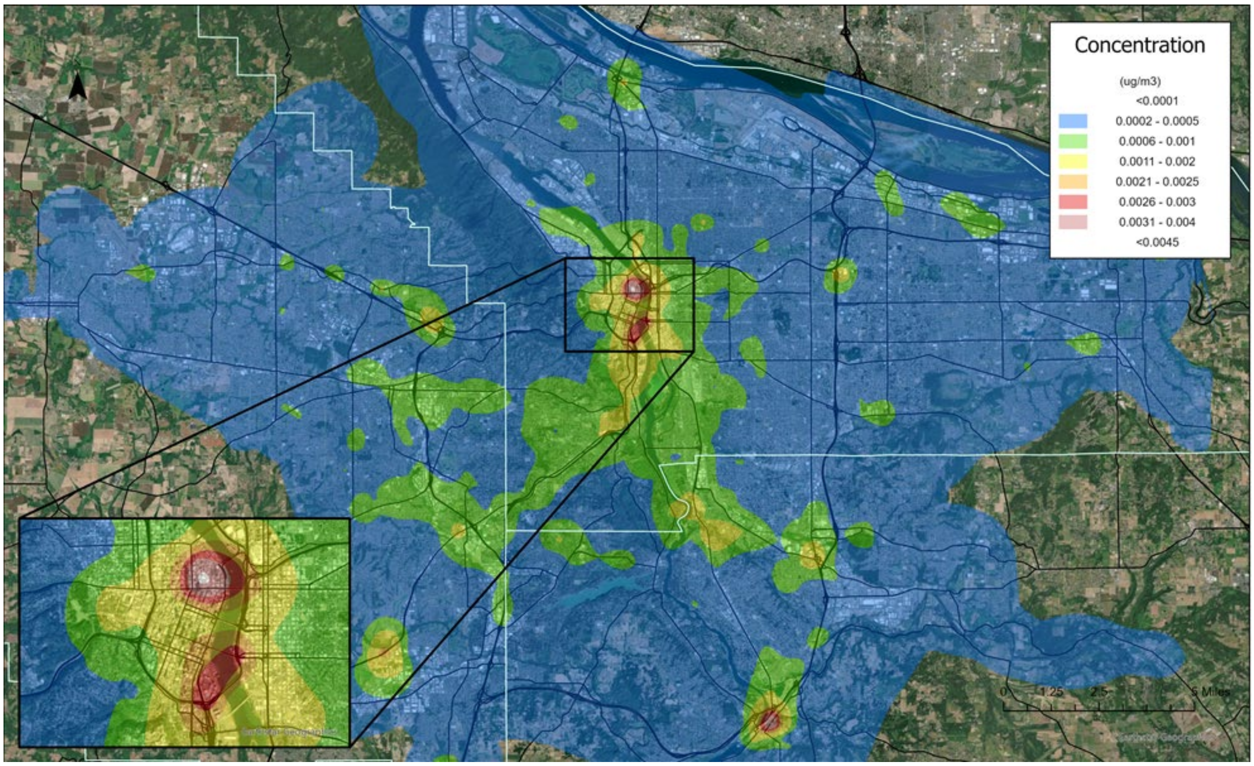

Figure 7. Modeled annually averaged Diesel PM levels from TriMet buses using petroleum diesel

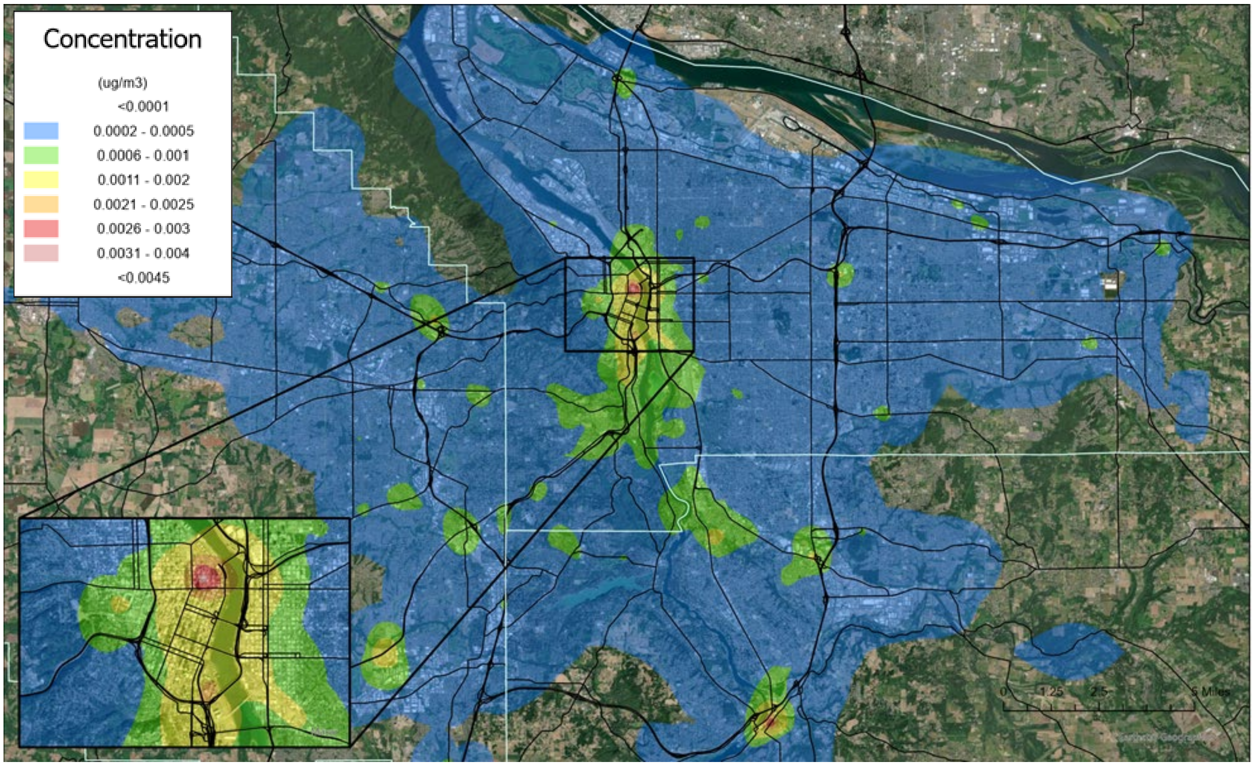

Figure 8. Modeled annually averaged Diesel PM levels from TriMet buses using R99 fuel (current practice).

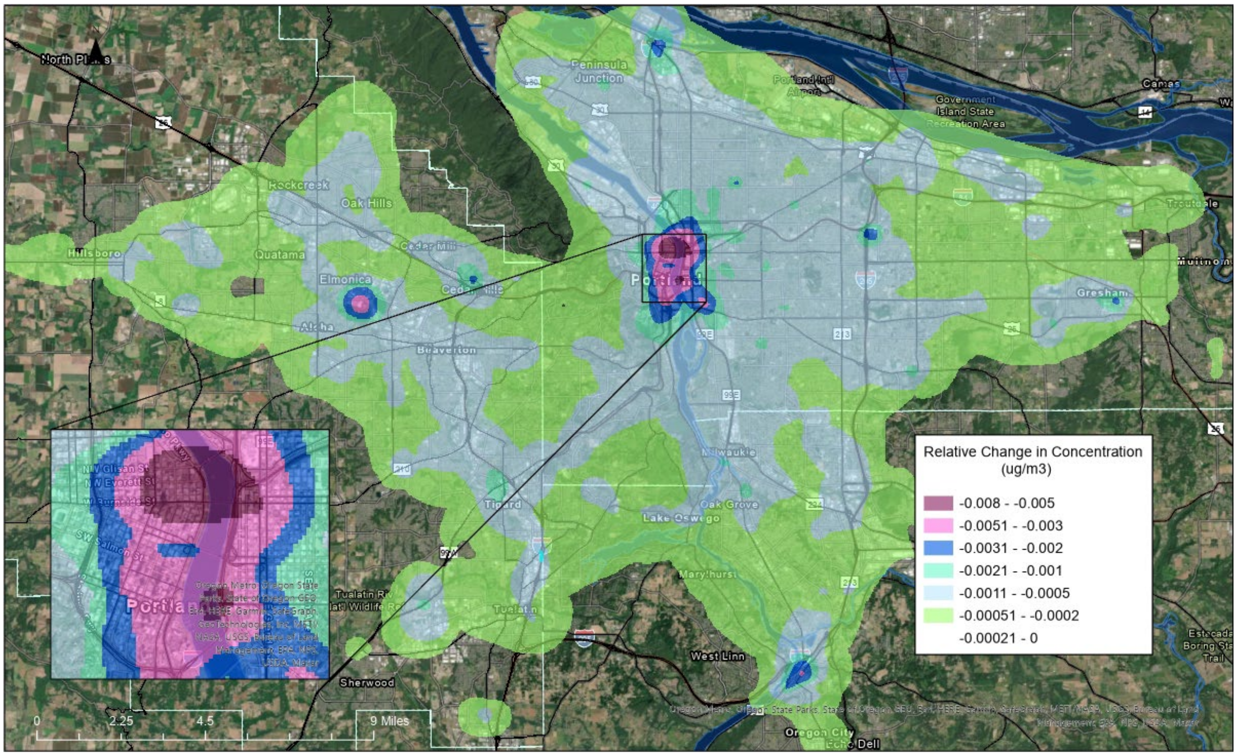

Figure 9. Change in Modeled annually averaged Diesel PM levels from TriMet buses between standard diesel and R99 fuel

While the reduction in Figure 9 is numerically small, it is important to keep in mind the DPM risk-based concentration threshold is 0.1 ug/m^3 for Oregon and 0.003 ug/m^3 for California.

RECOMMENDATIONS

Our goal for this project was to provide input to assist TriMet in determining a priority order for the transition of their fleet to electric power. Since diesel particulate matter is a strong contributor to cancer risk in the Portland metropolitan area, a focus on reducing this impact from buses would be highly beneficial.

Our analysis shows that downtown Portland is significantly impacted by the cumulative influence of the number of buses that travel through the downtown area. Given the high density of residents living downtown, this is an area of concern. Focusing on health impacts (see TMRE-rank ver1.xlsx tool) of individual routes, eastside Routes 8, 6, 75 and 12 are the most impactful routes. While we did not conduct socio-demographic analysis, it is likely that eastside bus routes impact vulnerable populations. Further analysis based on demographic considerations is recommended to supplement this work.

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