

Spatio-Temporal Analysis of the Roadside Transportation-Related Air Quality (StarTraq 2024): Time-Series Analysis

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Contents

Acknowledgments	vi
List of Figures	viii
List of Tables	x
Executive Summary	1
1. Introduction	2
2. Methodology	4
2.1 Air Quality Data and Study Area	4
2.2 Mobile Sources Emissions Inventory and VMT	6
2.3 Road network analysis	10
2.4 Land Cover Data	11
2.5 Time-Series Regression	12
3. Results	11
3.1 Air Quality in Fresno County	13
3.2 Mobile Sources Emissions Inventory	16
3.3 Road network data analysis in Fresno County (2016 – 2023)	47
3.4 Land Cover in Fresno County from 1985 to 2023	49
3.5 Time-Series Regression Results	57
4. Summary & Conclusions	60
Bibliography	63
About the Authors	66

List of Figures

Figure 1. GIS Database and Visualized Layers of Fresno County Datasets	6
Figure 2. Annual Average Concentrations of Criteria Air Pollutants (PM ₁₀ , PM _{2.5} , NO ₂ , SO ₂ , CO, and O ₃) in Fresno County from 1991 to 2023	13
Figure 3. Annual Daily Average VMT Trends by Vehicle Group in Fresno County (2000–2032)	17
Figure 4. Emission Trends by Fuel Type in Fresno County (2000–2032), EMFAC 2025 Model	18
Figure 5. Emission Trends by Vehicle Category in Fresno County (2000–2032)	21
Figure 6. Average Annual PM _{2.5} Emissions by Vehicle Category (2000–2032)	23
Figure 7. PM _{2.5} Emission Composition Over Time (2000–2032)	24
Figure 8. Average Annual PM ₁₀ Emissions by Vehicle Category (2000–2032)	25
Figure 9. PM ₁₀ Emission Composition Over Time (2000–2032)	26
Figure 10. Annual Average Daily PM _{2.5} Emissions by Vehicle Category in Fresno County	28
Figure 11. PM _{2.5} Emissions Trends by Vehicle Category in Fresno County (2000–2032)	29
Figure 12. Contribution to PM _{2.5} Emissions by Vehicle Category (Averages Across 2000–2032)	30
Figure 13. Annual Average Daily PM ₁₀ Emissions by Vehicle Category in Fresno County	32
Figure 14. PM ₁₀ Emissions Trends by Vehicle Category in Fresno County (2000–2032)	33
Figure 15. Contribution to PM ₁₀ Emissions by Vehicle Category (Averages Across 2000–2032)	34
Figure 16. Annual Average Daily NO _x Emissions by Vehicle Category in Fresno County	36
Figure 17. NO _x Emissions Trends by Vehicle Category in Fresno County (2000–2032)	37
Figure 18. Contribution to NO _x Emissions by Vehicle Category (Averages Across 2000–2032)	38
Figure 19. Annual Average Daily SO _x Emissions by Vehicle Category in Fresno County	40
Figure 20. SO _x Emissions Trends by Vehicle Category in Fresno County (2000–2032)	41
Figure 21. Contribution to SO _x Emissions by Vehicle Category (Averages Across 2000–2032)	42
Figure 22. Annual Average Daily CO Emissions by Vehicle Category in Fresno County	42
Figure 23. CO Emissions Trends by Vehicle Category in Fresno County (2000–2032)	43
Figure 24. Contribution to CO Emissions by Vehicle Category (Averages Across 2000–2032)	43
Figure 25. Annual Average Daily CO ₂ Emissions by Vehicle Category in Fresno County	45
Figure 26. CO ₂ Emissions Trends by Vehicle Category in Fresno County (2000–2032)	45

Figure 27. Contribution to CO ₂ Emissions by Vehicle Category (Averages Across 2000–2032)	46
Figure 28. Roadway Network Map Refers to Changes Between 2016 (Green) and 2023 (Purple)	48
Figure 29. Satellite View of Fresno County with Administrative Boundary	49
Figure 30. Land Use and Land Cover Changes in Fresno County (1990–2020)	50
Figure 31. Land Cover Changes in Fresno County By Category (1985–2023)	51
Figure 32. Census Tract-Level Analysis of Developed Land Expansion and Vegetation Loss in Fresno/Clovis Areas (1985–2023)	54
Figure 33. Detailed Map of Vegetation Changes by Parcel (1985–2023)	55
Figure 34. Land Cover Transition Area (1985–2023)	57

List of Tables

Table 1. Air Quality Monitoring Sites in Fresno County, California	4
Table 2. Grouping EMFAC Vehicle Categories for the VMT and Emission Analysis	8
Table 3. Summary of Key Changes in Land Cover (1985–2023)	50
Table 4. Land Use Transitions to Urban Classes: Herbaceous, Pasture, and Cropland Conversions (1985–2023)	56
Table 5. GLS-AR(1) Regression Results	57
Table 6. First-Difference Regression Results	58

Executive Summary

This report presents a comprehensive spatio-temporal analysis of roadside transportation-related air quality in Fresno County, California, from 1985 to 2023, using historical data and model-projected VMTs from 2024 to 2032. Leveraging geospatial data integration, on-road mobile source emissions inventories, criteria air pollutant annual averages throughout the Fresno County region, and land cover datasets, the study examines the long-term impacts of vehicle-related emissions, road network infrastructure development, and urban expansion on local air quality that are associated with significant impacts on human health and threaten public health.

Key findings indicate that while PM_{10} , $PM_{2.5}$, NO_x , SO_x , CO, and CO_2 emissions from on-road mobile sources have declined substantially due to regulatory programs and cleaner technologies, the contribution of passenger vehicles has become proportionally more significant in recent years. Spatial analysis of land cover changes reveals that over 130 km² of land, mostly cultivated crops, was converted to urban development, primarily in the Fresno/Clovis metro area.

On the Sierra Nevada side of Fresno County, the evergreen forest suffered the largest absolute loss of any category, decreasing by 730.5 km² (-24%), a sharp decline from around 2015 to 2023 that correlates with California's severe drought, wildfires, and tree mortality events. TIGER road data show stability in major road infrastructure, but the growth of low-density residential areas has increased vehicle miles traveled (VMT), further complicating air quality management.

These findings reinforce the importance of coordinated land-use planning, freight transportation regulations, and sustainable transportation infrastructure to ensure environmental equity and healthier communities in shaping sustainable urban futures across the San Joaquin Valley.

1. Introduction

Fresno County, located in the heart of California's San Joaquin Valley (SJV), faces some of the most persistent and severe air quality challenges in the United States. Despite the nation's strict auto emissions standards, Fresno and other cities in the San Joaquin Valley have ranked among the worst for air quality, with particulate matter (PM) levels exceeding federal and state clean air standards for decades. Characterized by its unique topography, a basin surrounded by the Sierra Nevada and Coastal Mountain ranges, and dominated by intensive agricultural production and major freight corridors, the region frequently exceeds state and federal standards for Particulate Matter (PM_{2.5}, PM₁₀) and Ozone (O₃). These pollutants pose significant public health risks, contributing to elevated rates of asthma, cardiovascular disease, and premature mortality among local populations.

Historically, on-road mobile sources, particularly heavy-duty diesel trucks transporting agricultural goods and freight along State Route 99 and Interstate 5, have been the primary drivers of this pollution burden. In response, the California Air Resources Board (CARB) has implemented some of the world's most aggressive air quality regulations, including the Truck and Bus Rule, the introduction of Ultra-Low Sulfur Diesel (ULSD), and the Clean Truck Check program. While these mandates have successfully targeted tailpipe exhaust, the region is simultaneously undergoing a profound physical transformation. Rapid population growth is driving the conversion of agricultural land into urban and suburban environments, altering traffic patterns, increasing Vehicle Miles Traveled (VMT), and modifying the landscape's natural capacity to mitigate pollution.

As engine technologies have advanced, the nature of transportation-related air pollution in Fresno County is shifting. Preliminary evidence suggests a source crossover, where non-exhaust emissions (brake and tire wear) from passenger vehicles are becoming as significant as, or more significant than, traditional diesel exhaust. Furthermore, the expansion of the built environment, characterized by the growth of impervious surfaces and the loss of vegetative cover, threatens to offset technological gains by facilitating dust resuspension and exacerbating the urban heat island effect. Understanding this complex, interacting dynamics requires more than a snapshot of current conditions; it demands a comprehensive, multi-decadal analysis of how emissions, infrastructure, and land use have evolved simultaneously.

This report aims to provide a holistic assessment of Fresno County's environmental trajectory over the last three decades. The primary aim of this study is to assess long-term trends in transportation-related air pollutants (TRAPs) and their relationship to changes in land cover, road networks, and vehicle activity over the past three decades. Building upon previous StarTraq projects, this research constructs a detailed geospatial database that integrates EMFAC mobile emissions, air quality trends (US EPA), TIGER road datasets, and National Land Cover

Database (NLCD) classifications. This allows for a granular understanding of how urban expansion, vehicle types, and infrastructure growth influence Fresno County's air quality.

1. To evaluate long-term air quality trends of criteria air pollutants that are historically associated with on-road mobile emissions in Fresno County from 1991 to 2023, from regional air monitoring data for PM_{2.5}, PM₁₀, NO_x, SO_x, CO, and O₃.
2. To evaluate long-term emission trends (2000–2032), the EMFAC 2025 model was used to quantify the effectiveness of mobile-source regulations on PM_{2.5}, PM₁₀, NO_x, SO_x, CO, and CO₂, and to identify shifts in source contributions between heavy-duty freight and passenger vehicles from 2000 to 2032.
3. To analyze infrastructure stability, assess changes in the physical road network using TIGER/Line data to determine if capacity expansion is keeping pace with utilization.
4. To quantify land cover transitions (1985–2023), use the National Land Cover Database (NLCD) to map the spatial extent of urbanization, specifically measuring the conversion of agricultural and forest lands into developed urban areas.

By identifying spatial patterns in air quality and trends in mobile emissions, the study provides data-driven insights for planners and policymakers focused on improving air quality, public health, and sustainable transportation systems in California's inland communities. By synthesizing these domains—air quality, mobile emissions, road network infrastructure, and land cover—this report provides a detailed evidentiary basis for understanding the successes of past policy, the emerging challenges of the future built environment, and avenues for public health improvement. The research developed a geospatial database that can leverage transportation-related pollution data in health datasets for time-series analysis to examine how changes in regional commercial VMT and roadway networks have impacted the pollution burden and public health concerns over decades, for healthier communities.

2. Methodology

2.1 Air Quality Data and Study Area

Air Quality Monitoring Sites

The study focused on six key pollutants regulated under the U.S. Clean Air Act: particulate matter (PM₁₀ and PM_{2.5}), nitrogen dioxide (NO₂), sulfur dioxide (SO₂), carbon monoxide (CO), and ozone (O₃). Fresno County, located in California's San Joaquin Valley, has maintained an extensive air quality monitoring network since 1959. Historically, 31 monitoring sites have been established across the county to measure ambient concentrations of major criteria air pollutants. Of these, 18 sites have been closed, while 13 active monitoring stations were selected for this study based on data completeness and representativeness of regional air quality conditions for the study period. The selected sites represent a broad spectrum of land-use types and elevation gradients, capturing both urban-industrial environments (e.g., Fresno Foundry, Clovis Villa) and rural-agricultural zones (e.g., Huron, Tranquility, Table Mountain). Together, these 13 monitoring stations provide comprehensive spatial coverage of Fresno County's air quality conditions, enabling the assessment of long-term trends and pollutant distributions relevant to both regulatory compliance and environmental health studies. These data were obtained from the U.S. EPA's Air Quality System (AQS) database for the selected Fresno County monitoring sites listed in Table 1.

Table 1. Air Quality Monitoring Sites in Fresno County, California

Site ID	Latitude	Longitude	Local Site Name	Land Use & Location Setting
6	36.837448	-119.85126	Fresno-Herndon	
7	36.705474	-119.74133	Fresno-Drummond	Commercial/Suburban
8	36.781333	-119.77319	3425 N First St, Fresno	Residential/Suburban
11	36.785380	-119.77321	Fresno – Garland	Commercial/Urban and Center City
242	36.841592	-119.87474	Fresno-Sky Park	Residential/Suburban
500	36.985119	-119.65834	Table Mountain Air Site	Agricultural/Rural
2008	36.198672	-120.10110	Huron	Residential/Rural
2009	36.634225	-120.38233	Tranquility	Agricultural/Rural
2016	36.710833	-119.77700	Fresno-Foundry	Industrial/Urban and Center City
4001	36.597442	-119.50366	Parlier	
5001	36.819449	-119.71643	Clovis-Villa	Residential/Urban and Center City
5025	36.726390	-119.73300	Fresno-Pacific	Residential/Urban and Center City
9000	37.220640	-119.15556	Kaiser Wilderness	Forest/Rural

Data Source and Study Area

Annual air pollutant concentrations for Fresno County, California, were constructed data from the U.S. Environmental Protection Agency (EPA) Air Quality System (AQS). Annual monitor-level summary files were downloaded from the EPA AirData portal (https://aqs.epa.gov/aqsweb/airdata/download_files.html#Annual) and processed in R (version 4.3) for the period 1990 through 2024. The study analyzed six major criteria pollutants identified by their AQS parameter codes: carbon monoxide (CO, 42101), sulfur dioxide (SO₂, 42401), nitrogen dioxide (NO₂, 42602), ozone (O₃, 44201), particulate matter ≤10 μm (PM₁₀, 81102), and particulate matter ≤2.5 μm (PM_{2.5}). PM_{2.5} concentrations were reported under two parameter codes (81104 and 88502) and were merged into a single synthetic code, “81104X,” for analysis.

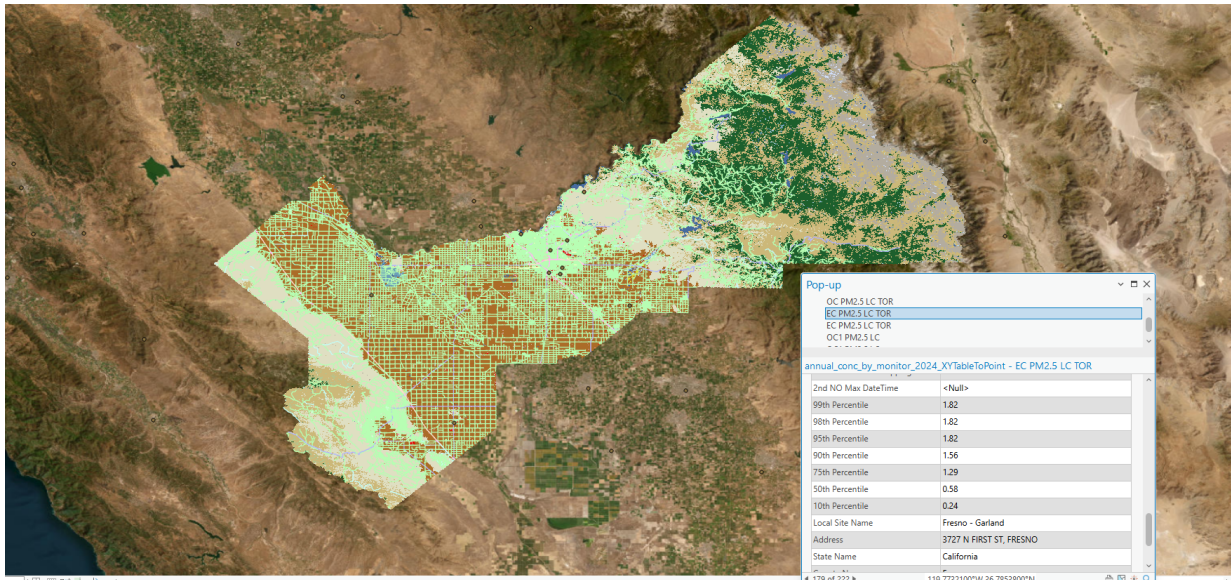
Data Filtering and Quality Control

To ensure data consistency and representativeness, only observations meeting strict spatial, temporal, and quality filters were retained. The criteria were as follows:

1. Geographic scope: Location limited to Fresno County, California.
2. Completeness criteria: To maintain data quality for understanding air quality trends throughout the study period, monitors were required to have a completeness indicator of “Y” and an observation percentage greater than 75%.
3. Regulatory Standard Filtering: For CO, SO₂, NO₂, O₃, and PM₁₀, data were restricted to specific regulatory standards to ensure consistency (e.g., “Ozone 8-Hour 2008” for O₃ and “PM₁₀ 24-hour 2006” for PM₁₀). Conversely, for the combined PM_{2.5} group, all available pollutant standards were retained to maximize data availability.

After the data filtering procedure, no monitor-pollutant combinations qualified for inclusion for the endpoint years of 1990 and 2024. Consequently, the final analyzed time series covers the period 1991–2023.

Figure 1. GIS Database and Visualized Layers of Fresno County Datasets



Data Aggregation and Visualization

The aggregation from monitor-level data to county-level annual averages followed two main stages:

1. **Site-Level Aggregation:** For each monitoring site, year, and pollutant group, a single annual mean was calculated by averaging the arithmetic mean values. This procedure consolidated duplicate rows (e.g., those arising from multiple metric definitions) into a single representative value for each site.
2. **County-Level Aggregation:** Site-level means were aggregated to produce a single county-wide value for each pollutant and year. The mean concentration was used as the principal indicator for long-term trend analysis, while median concentration and n_{sites} were retained for diagnostic and interpretive purposes.

Pollutant-specific annual mean concentrations were plotted as a time series for each pollutant, illustrating trends in Fresno County's ambient air quality between 1991 and 2023 (Figure 1).

2.2 Mobile Sources Emissions Inventory and VMT

County-level information on population, vehicle activity, emissions from on-road mobile sources, and Vehicle Miles Traveled (VMTs) in Fresno County was obtained from the California Air Resources Board's Mobile Source Emissions Inventory (MSEI) for the years 2000 to 2032 (CARB 2025a, <https://ww2.arb.ca.gov/our-work/programs/msei/mobile-source-emissions-inventory>). The VMT data from 2000 to 2023 are based on actual data, while those from 2024 to 2032 are model-based projections. Data on VMT and emissions by vehicle type, fuel type, and pollutant

(including PM_{2.5}, PM₁₀, NO_x, SO_x, CO, and CO₂) were downloaded from the EMFAC 2025 v2.0.0 model. This emission factor tool estimates emissions from on-road mobile sources in California. All emission units are reported in tons per day (CARB 2025b, <https://arb.ca.gov/emfac/emissions-inventory>). The EMFAC model utilizes 55 detailed vehicle classifications defined by vehicle function, fleet type (e.g., Public vs. Utility), and weight class. To facilitate annual trend visualization and comparative emission analysis, these detailed classifications are grouped into 13 umbrella groups by weight and vehicle type (Table 2).

Table 2. Grouping EMFAC Vehicle Categories for the VMT and Emission Analysis

Umbrella group	Vehicle classification	Description
Daily-commute & household Private-use cars, light trucks, SUVs, and motorcycles used for commuting or errands	LDA	Passenger cars (commute/errands)
	LDT1	Small light-duty trucks/SUVs (GVWR < 6,000 lbs; ETW ≤ 3,750 lbs)
	LDT2	Large light-duty trucks/SUVs (GVWR < 6,000 lbs; ETW 3,751–5,750 lbs)
	MDV	“Medium-duty” light vehicles (GVWR 6,001–8,500 lbs)
	MCY	Motorcycles
Out-of-state operating in CA Trucks registered outside CA but operating in-state; grouped by proximity	T6 OOS Class 4	OOS medium truck in CA, Class 4
	T6 OOS Class 5	OOS medium truck in CA, Class 5
	T6 OOS Class 6	OOS medium truck in CA, Class 6
	T6 OOS Class 7	OOS medium truck in CA, Class 7
	T7 NOOS Class 8	Neighboring OOS heavy truck in CA
	T7 NNOOS Class 8	Non-neighboring OOS heavy truck in CA
Local commercial delivery & service Small business vehicles for service and delivery operating exclusively within CA	LHD1 Other	Light heavy-duty, 8,501–10,000 lbs, in-state business use
	LHD2 Other	Light heavy-duty, 10,001–14,000 lbs, in-state business use
	T6 Instate Delivery Class 4	In-state delivery, Class 4
	T6 Instate Delivery Class 5	In-state delivery, Class 5
	T6 Instate Delivery Class 6	In-state delivery, Class 6
	T6 Instate Delivery Class 7	In-state delivery, Class 7
	T6 Instate Other Class 4	In-state other commercial, Class 4
	T6 Instate Other Class 5	In-state other commercial, Class 5
	T6 Instate Other Class 6	In-state other commercial, Class 6
Interstate / IRP-registered Commercial trucks with apportioned IRP registration operating across state lines	T6 CAIRP Class 4	IRP (interstate) medium truck, Class 4
	T6 CAIRP Class 5	IRP (interstate) medium truck, Class 5
	T6 CAIRP Class 6	IRP (interstate) medium truck, Class 6
	T6 CAIRP Class 7	IRP (interstate) medium truck, Class 7
	T7 CAIRP Class 8	IRP (interstate) heavy truck, Class 8
Tractors & vocational heavies (in-state) Includes semis and Class 8 vocational trucks such as cement mixers	T6 Instate Tractor Class 6	In-state tractor (semi), Class 6
	T6 Instate Tractor Class 7	In-state tractor (semi), Class 7
	T7 Tractor Class 8	Tractor (semi), Class 8
	T7 Single Concrete/Transit Mix Class 8	Single-unit concrete/transit-mix
	T7 Single Dump Class 8	Single-unit dump

Umbrella group	Vehicle classification	Description
	T7 Single Other Class 8	Other single-unit vocational
Solid-waste & municipal services	T7 SWCV Class 8	Solid-waste collection vehicle Specialized garbage trucks with frequent stops and high engine load
Government / public fleets Government vehicles across all duty classes, treated separately due to procurement policies	LHD1 Public	Light heavy-duty, 8,501–10,000 lbs, public
	LHD2 Public	Light heavy-duty, 10,001–14,000 lbs, public
	T6 Public Class 4	Public fleet, Class 4 (14,001–16,000 lbs)
	T6 Public Class 5	Public fleet, Class 5 (16,001–19,500 lbs)
	T6 Public Class 6	Public fleet, Class 6 (19,501–26,000 lbs)
	T6 Public Class 7	Public fleet, Class 7 (26,001–33,000 lbs)
	T7 Public Class 8	Public fleet, Class 8 (≥33,001 lbs)
Transit & school buses Includes school, urban, charter, and intercity buses with high idle-stop cycles	SBUS	School buses
	UBUS	Urban transit buses
	OBUS	Other/charter/shuttle buses
	Motor Coach	Intercity/tour coaches
	All Other Buses	Misc. bus types not above
Fuel-specific heavy trucks (gasoline)	T6TS	Medium heavy-duty gasoline
	T7IS	Medium and heavy gasoline trucks are separated due to emission profile (most others are diesel)
Port drayage Short-haul Class 8 trucks for moving containers between ports and depots	T7 POAK Class 8	Port of Oakland drayage
	T7 POLA Class 8	Port of Los Angeles drayage
	T7 Other Port Class 8	Other CA ports drayage
Recreational/pleasure	MH	Motorhomes and RVs used seasonally for travel, with high idling and low frequency
Special operation (non-movement)	PTO	Power take-off (engine powers equipment) Stationary emissions from power take-off operations (e.g. cranes, pumps)
Utility fleets Trucks used by electric, water, and telecom companies; includes high PTO use	T6 Utility Class 5	Utility truck, Class 5
	T6 Utility Class 6	Utility truck, Class 6
	T6 Utility Class 7	Utility truck, Class 7
	T7 Utility Class 8	Utility truck, Class 8

2.3 Road Network Analysis

Topologically Integrated Geographic Encoding and Referencing (TIGER) road data are available from a county-based line database maintained by the United States Census Bureau. The past 30 years of the Census MAF/TIGER database were used to examine changes in primary and secondary roads in Central Valley counties using the MAF/TIGER Feature Classification Code (MTFCC) and Route Type Code (RTTYP). The TIGER/Line shapefiles provide detailed, county-based geographic line data and are widely used for transportation and urban planning studies. For data collection, TIGER/Line road shapefiles were downloaded for the years 2016, 2018, 2020, 2021, 2022, and 2023. Data were processed and analyzed using MAF/TIGER Feature Classification Codes (MTFCC), which categorize roads by type. In addition to line attributes, Route Type Codes (RTTYP) were referenced to differentiate between signed routes (e.g., U.S. highways) and local roads. Road segments were classified using MTFCC codes:

- S1100 – Primary roads (e.g., interstates and major highways)
- S1200 – Secondary roads
- S1400 – Local neighborhood and rural roads
- S1500 – Vehicular trails (4WD, unpaved)
- S1630 – Ramp roads
- S1640 – Service drives, parking lot roads
- S1710 – Walkways, pedestrian trails
- S1730 – Stairways
- S1740 – Alleys
- S1750 – Private roads (driveways, etc.)
- S1780 – Roads with special characteristics (tunnels, bridges)

These codes enabled consistent categorization and tracking of infrastructure changes. For analysis, total road lengths in kilometers were aggregated by MTFCC code for each year. Comparative analysis was performed for the 2018–2023 period to assess network expansion, contraction, or stability. A spatial overlay map was created comparing 2016 (green) and 2023 (purple) road layers to visualize physical changes in the road network.

2.4 Land Cover Data

To characterize long-term changes in surface composition and their potential impact on regional air quality, National Land Cover Database (NLCD) raster datasets were acquired for the period spanning 1985 to 2023. The NLCD provides standardized, multi-temporal land cover classifications at a 30-meter spatial resolution, enabling consistent analysis of landscape dynamics across the study timeline.

For spatial refinement, the continental NLCD rasters were clipped to the Fresno County boundary using a dissolved census tract shapefile. This processing step removed extraneous data outside the region of interest, ensuring that subsequent statistical analyses focused exclusively on pixels within the defined study domain.

Land Cover Classification and Air Quality Associations

To evaluate the relationship between landscape composition and atmospheric conditions, NLCD land cover classes were categorized based on their theoretical capacity to act as either emission sources or deposition sinks for air pollutants. The specific associations evaluated are as follows:

- **Developed Land (Classes 21–24):** This category aggregates low-, medium-, and high-intensity development, representing impervious and semi-impervious urban surfaces. These areas are conceptually linked to degraded air quality, driven by high concentrations of anthropogenic emissions from transportation, industrial operations, and residential heating. Furthermore, the displacement of vegetation by impervious surfaces in these zones reduces the landscape's natural capacity to remove pollutants.
- **Barren Land (Class 31):** This category comprises areas of exposed soil, rock, or sand with less than 15% vegetation cover. In the Central Valley's semi-arid environment, these surfaces can serve as reservoirs for windblown dust and coarse particulate matter (PM₁₀), particularly during dry, windy conditions.
- **Forest and Shrubland (Classes 41–43, 52):** This group encompasses deciduous, evergreen, and mixed forests, as well as shrublands and scrublands. These vegetated classes are primarily associated with improved air quality. The canopy structure facilitates the interception and deposition of particulate matter, while physiological processes facilitate stomatal uptake of gaseous pollutants such as nitrogen dioxide (NO₂) and ozone (O₃).
- **Agricultural and Herbaceous Land (Classes 71, 81, 82):** This group comprises grasslands, pastures, and cultivated crops. These lands play a complex dual role: While vegetation in these zones provides surfaces for pollutant deposition and dust suppression, agricultural operations (e.g., tillage, fertilization) can act as sources of particulate matter and ammonia (NH₃) emissions.

- Wetlands (Classes 90, 95): This group includes woody and emergent herbaceous wetlands. These areas contribute to local microclimate regulation. They may help filter airborne contaminants through their high surface roughness and biological uptake.

The processed land cover data support temporal and spatial correlation analysis with air pollution metrics (e.g., PM_{2.5}, NO_x), helping to identify land-use patterns that may influence or mitigate local air quality trends in Fresno County over time.

2.5 Time-Series Regression

To formally evaluate the relationship between transportation activity, urban development, and air quality, we estimated time-series regression models using generalized least squares (GLS) with autoregressive error structures. Annual observations from 2000 to 2023 were analyzed.

The primary specification is:

$$Y_t = \beta_0 + \beta_1 \text{HouseholdVMT}_t + \beta_2 \text{FreightVMT}_t + \beta_3 \text{Urbanization}_t + \varepsilon_t,$$

where

- Y_t represents annual pollutant concentration (PM_{2.5}, PM₁₀, or NO₂),
- HouseholdVMT captures passenger travel demand,
- FreightVMT represents aggregated commercial vehicle activity, and
- Urbanization reflects developed high, medium, and low land intensity.

To account for temporal dependence commonly observed in environmental time-series data, the error term follows an autoregressive (AR) process:

$$\varepsilon_t = \rho \varepsilon_{t-1} + u_t$$

This GLS–AR(1) framework produces efficient and unbiased parameter estimates in the presence of serial correlation. To assess whether observed relationships are driven by shared long-term trends, we additionally estimate first-difference models:

$$\Delta Y_t = \alpha_0 + \alpha_1 \Delta \text{HouseholdVMT}_t + \alpha_2 \Delta \text{FreightVMT}_t + \alpha_3 \Delta \text{Urbanization}_t + \eta_t$$

These models evaluate whether year-to-year changes in transportation and land use are associated with changes in pollutant concentrations. All predictors are standardized (z-scores) to facilitate interpretation and comparability of coefficients.

3. Results

3.1 Air Quality in Fresno County

Each criteria air pollutant's trajectory depicts long-term progress toward improved air quality under evolving federal and state standards, providing a consistent, quality-assured dataset for policy and health impact analyses. Figure 2 displays trajectories for PM₁₀, PM_{2.5}, NO₂, SO₂, CO, and O₃.

Figure 2. Annual Average Concentrations of Criteria Air Pollutants (PM₁₀, PM_{2.5}, NO₂, SO₂, CO, and O₃) in Fresno County from 1991 to 2023

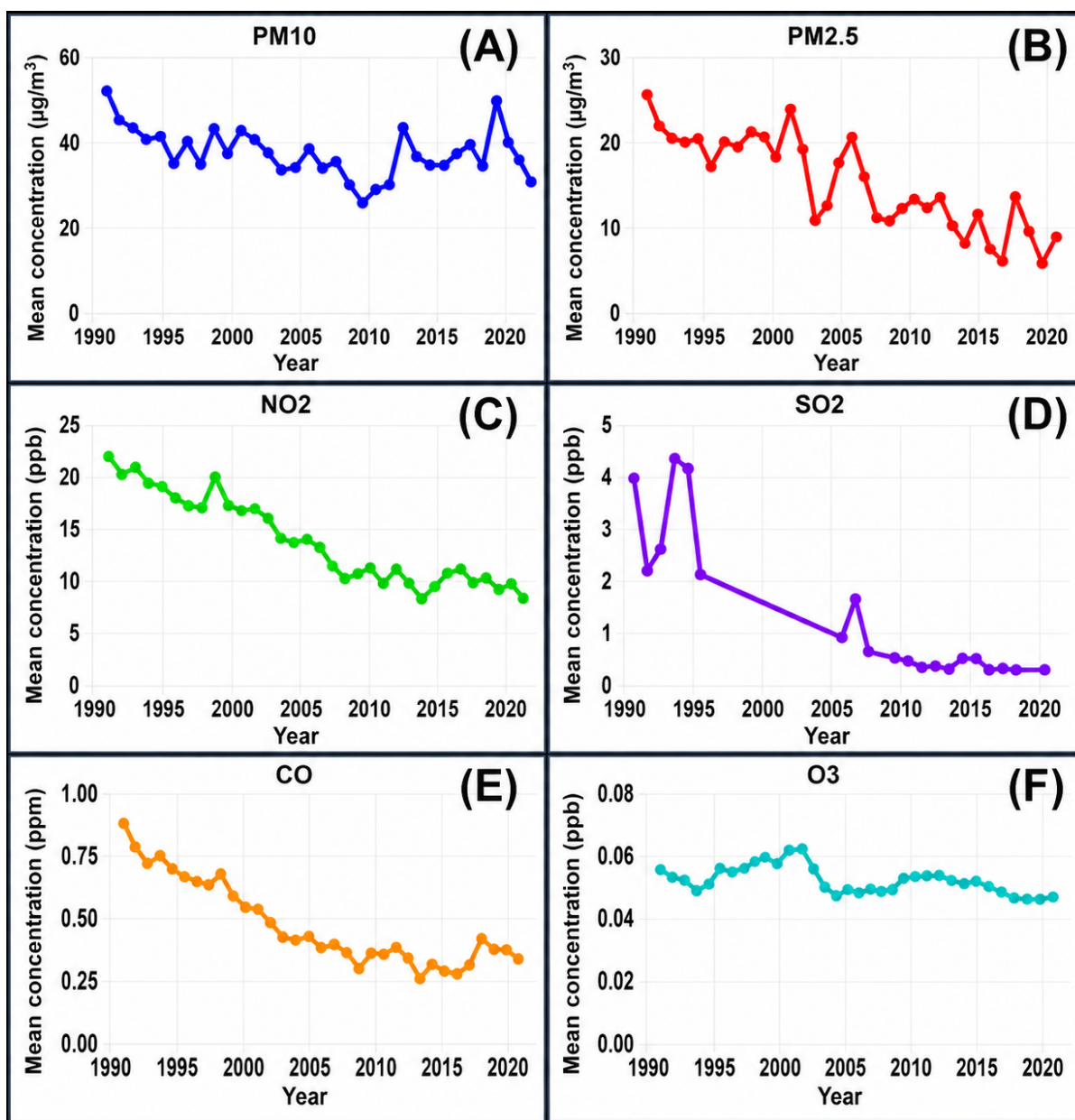


Figure 2 illustrates the long-term annual mean concentrations of six criteria air pollutants, PM₁₀, PM_{2.5}, NO₂, SO₂, CO, and O₃, for Fresno County, California, over the period 1991–2023. The six annual time series plots demonstrate significant improvements in regional air quality in Fresno County over the past three decades. While the specific rates of decline vary by pollutant, the overall long-term trends confirm the effectiveness of federal and state emissions control programs, technological advancements, and regulatory compliance efforts, particularly those targeting mobile sources.

PM₁₀, Coarse Particulate Matter

Among the six criteria air pollutants, PM₁₀ shows the least improvement overall, exhibiting a fluctuating pattern rather than a clear, smooth decline. However, PM₁₀ concentrations (Figure 2A) exhibit a notable declining trend from approximately 55–60 µg/m³ in the early 1990s to around 30 µg/m³ by 2023. Although year-to-year variability remains, the overall reduction of roughly 40–50% demonstrates the effectiveness of dust control, industrial emission reductions, and agricultural management measures implemented since the early 2000s. While transportation-related PM₁₀ has decreased, the major proportion of PM₁₀ in Fresno is influenced by resuspended dust from road, construction, and agricultural activities, driven by prolonged drought conditions in California (2011–2017, 2020–2023) and wildfire-impacted periods (2016–2025)

PM_{2.5}, Fine Particulate Matter

PM_{2.5} concentrations (Figure 2B) show a stronger downward long-term trend than PM₁₀, particularly after 2005. Average annual concentrations decreased from around 25–30 µg/m³ in the early 1990s to below 12 µg/m³ in recent years, meeting the U.S. EPA’s annual PM_{2.5} standard (12 µg/m³). The most significant declines coincide with the introduction of California Air Resources Board’s (CARB) diesel engine standards, wood-burning restrictions, and agricultural equipment retrofits. A notable decline from roughly 1999 to 2011 was observed, followed by a plateau or occasional spikes during 2017–2023. Cleaner diesel truck standards drove early gains. However, recent volatile trends are heavily influenced by wildfire smoke events and secondary aerosol formation (ammonium nitrate) during winter inversions. These events, independent of direct emission from mobile sources, create spikes in the annual average that can mask the underlying reduction in anthropogenic tailpipe emissions. Collectively, reductions in both PM fractions indicate substantial progress toward mitigating fine- and coarse-particle pollution sources in the San Joaquin Valley.

Nitrogen Dioxide (NO₂)

NO₂ (Figure 2C) has declined steadily and consistently since the early 1990s, from mean concentrations near 20 ppb to below 10 ppb. This represents approximately a 50% reduction

over the 30-year record. The NO₂ time series likely exhibits the most consistent and precipitous decline of all six pollutants. The NO₂ decline reflects the transition to cleaner vehicle fleets, adoption of low-NO_x combustion technologies, and regional transportation emission controls. Current levels remain well below the annual NO₂ standard (53 ppb), demonstrating sustained improvements in emissions from vehicular and stationary sources. This trend reflects the successful implementation of the California Air Resources Board's (CARB) mobile source regulations. As older, high-NO_x vehicles have been retired and replaced by cleaner engines (equipped with Three-Way Catalysts and Selective Catalytic Reduction), ambient NO₂ concentrations have collapsed, often dropping by over 60–70% from their 1990s peaks.

Sulfur Dioxide (SO₂)

SO₂ concentrations (Figure 2D) display the most dramatic reduction, dropping from 3–4 ppb in the early 1990s to near-zero levels after 2010. This sharp decline corresponds to reductions in sulfur content in fuels, industrial process controls, and the phase-out of high-sulfur diesel and refinery operations. Since 2015, annual averages have remained below 0.5 ppb, indicating near-complete elimination of SO₂ as a local air quality concern in Fresno County. The SO₂ series showed a low-magnitude, flat trend that hovers just above zero for the entire period, while the annual mean of the national standard is 10 ppb. SO₂ emissions from transportation were reduced decades ago because California mandated stricter Ultra-Low Sulfur Diesel (ULSD) and cleaner gasoline before the rest of the nation did.

Carbon Monoxide (CO)

CO levels (Figure 2E) have declined steadily from 0.8 ppm in 1990 to roughly 0.3 ppm in 2023, amounting to a >60% reduction. Improvements are primarily attributed to vehicular emission-control technologies, including catalytic converters and oxygenated-fuel efficiency enhancements, as well as transportation management programs within the Fresno metropolitan area. CO concentrations have remained far below the 1-hour (35 ppm) and 8-hour (9 ppm) federal standards since the mid-2000s. The CO plot serves as a historical benchmark for regulatory success, showing that this pollutant has been effectively eliminated as a major health threat in the region for the last 15 years.

Ozone (O₃)

Unlike the other pollutants, ozone (Figure 2F) shows a relatively stable trend over the study period, fluctuating between 0.04 and 0.08 ppm. The ozone trend, as the 8-hour maximum average, typically shows a slower, bumpier decline than NO₂. A gradual downward trend is masked by significant year-to-year variability. While O₃ formation depends on complex photochemical reactions involving NO_x and VOCs, its persistence suggests that secondary pollutant formation processes remain influenced by meteorological conditions and regional

precursor transport. However, stabilization at lower levels after 2010 suggests some benefit from concurrent NO_x reductions and emission-control measures. The peaks are lower today than in the 1990s. While ozone precursors (NO_x and VOCs) have dropped significantly, ozone formation is highly non-linear and dependent on heat and sunlight. Hotter summers have partially offset the gains from reduced emissions, slowing the rate of improvement.

Overall, Fresno County has experienced marked improvements in air quality between 1991 and 2023, particularly for PM_{2.5}, PM₁₀, NO₂, SO₂, and CO. These declines reflect the cumulative impacts of state and federal air quality regulations, technological advancements, and regional emissions-reduction initiatives. The steepest reductions are observed in primary combustion pollutants (NO₂, CO), which directly correlate with mobile-source regulations. Despite these successes, secondary air pollutants produced by photochemical reactions, namely ozone (O₃), remain a persistent challenge, necessitating continued focus on strategies to reduce precursors and on climate-adaptive air quality management. Coarse particles (PM₁₀) also remain a challenge, likely influenced by resuspended dust from non-point sources and wildfire smoke.

3.2 Mobile Sources Emissions Inventory

Vehicle Mile Traveled (VMTs)

Figure 3A shows that the daily-commute & household group (black line) accounts for the overwhelming majority (84.6%) of the annual average daily VMT in Fresno County. VMT for this group consistently ranges from 14.4 to 19 million miles, showing a gradual upward trend from 2000 to 2025. A sharp decline of 6 million miles in 2020 (a 16% drop) significantly reflected the impact of the COVID-19 pandemic on personal travel. Following this, the VMT rebounded in 2021 to about 97% of 2019 VMT levels. The trend has stabilized near 19 million miles, with projections estimating a slow increase of less than 1% per year through 2032.

Figure 3. Annual Daily Average VMT Trends by Vehicle Group in Fresno County (2000–2032)

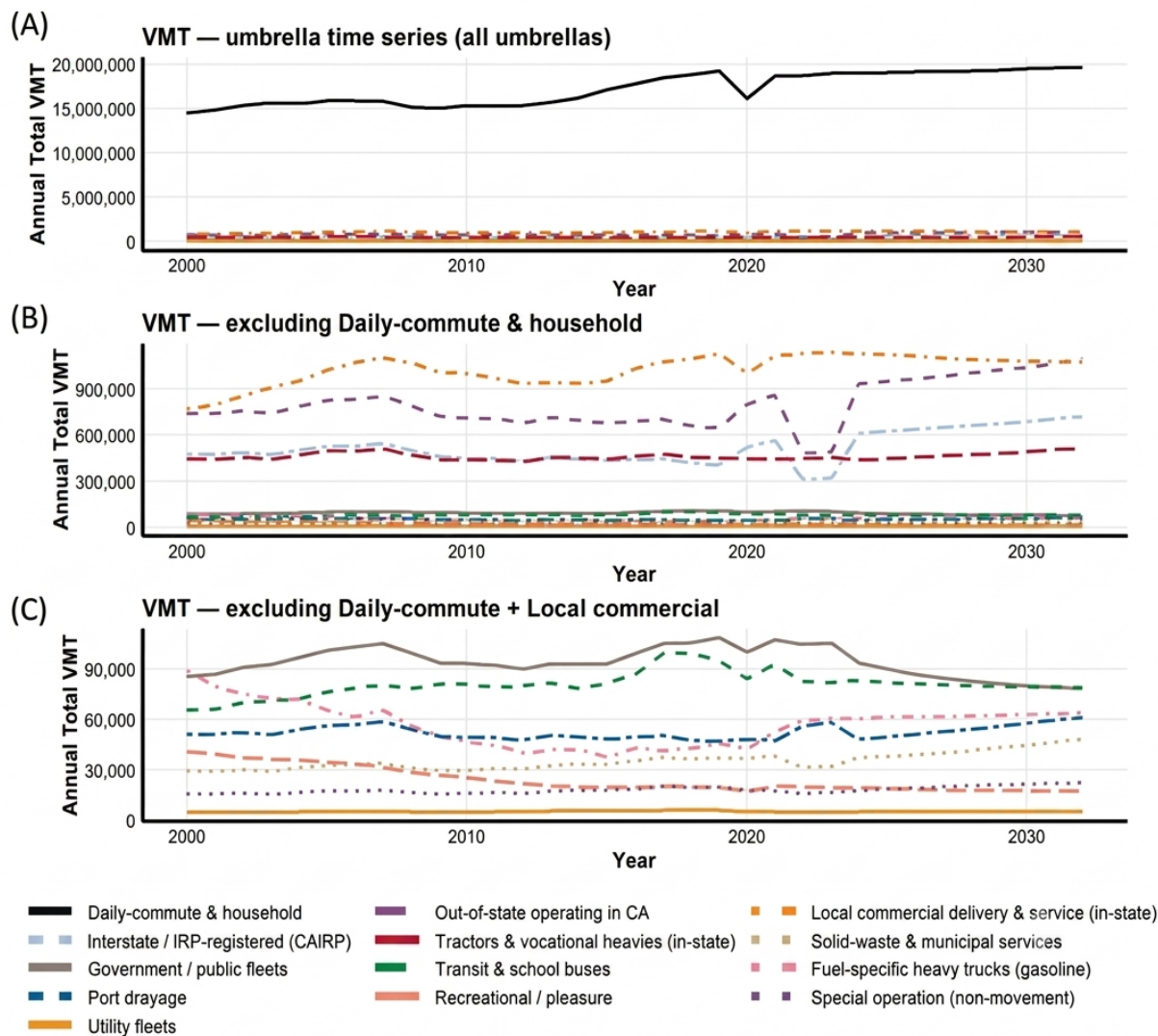
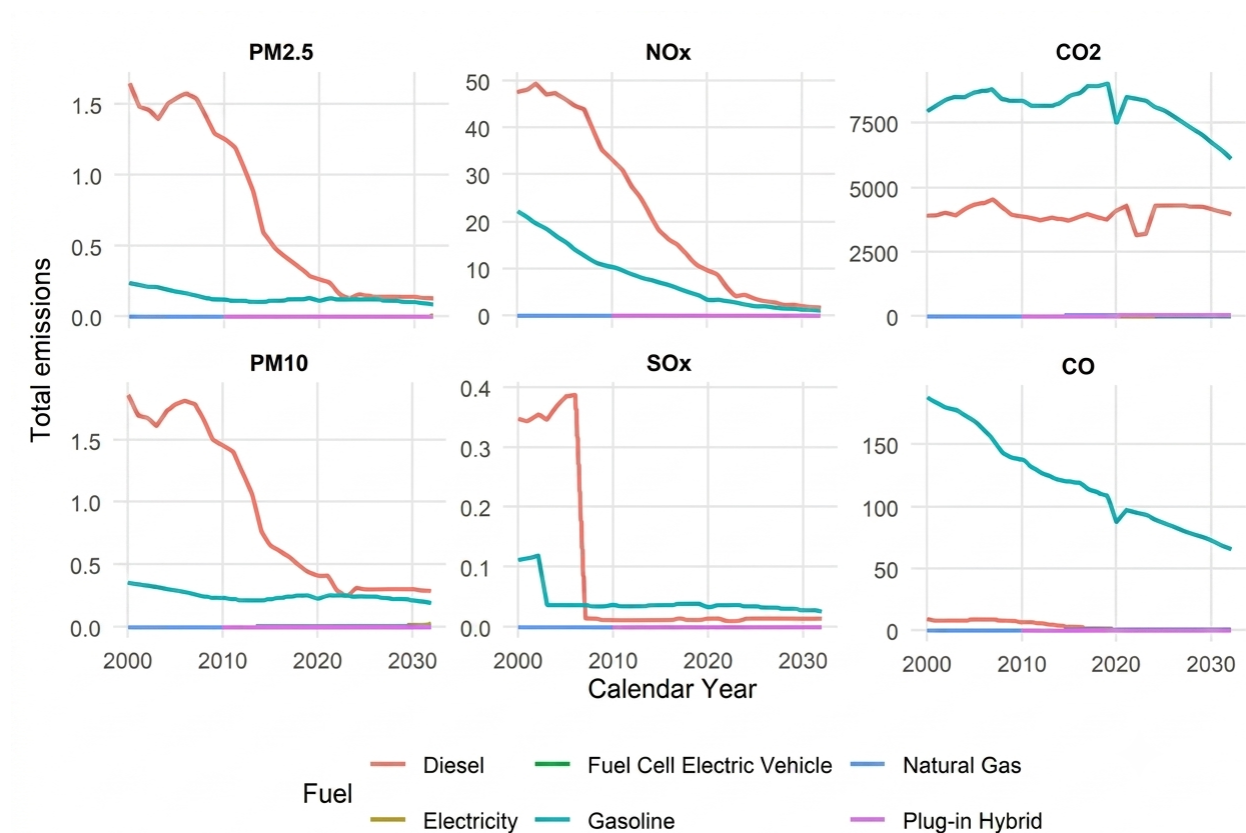


Figure 3B focuses on the next tier of vehicle groups of four, primarily associated with goods movement and logistics, with VMTs ranging roughly from 314,000 to 1.1 million miles. The local commercial delivery & service (in-state) group (orange dot-dash line) is the largest in this tier, accounting for 5.1% of total VMT. It shows a general upward trend and has exceeded 1 million miles since 2016, except for a 12% decrease in 2020. The out-of-state operating in CA (purple dashed line, 3.7%) and interstate/IRP-registered (light blue dashed line, 2.4%) groups exhibit volatile patterns, with relatively flat trends until 2021, followed by a sharp 44 % decline in 2022. Both are projected to rebound sharply by 2024, with out-of-state freight VMT expected to surpass pre-pandemic levels and reach new highs post-2024. In contrast, tractors & vocational heavies (in-state) (red dashed line, 2.3%) show a more stable pattern, maintaining a consistent baseline around 450,000 miles, with smaller fluctuations compared to interstate categories.

Figure 3C illustrates the eight lower-tier groups, where VMTs range from 4,500 to 108,000 miles. Among them, government/public fleets (brown solid line), transit & school buses (green dashed line), and solid wastes & municipal services (light brown dotted line) show moderate growth of 5%, 25%, and 29%, respectively, between 2000 and 2025. In contrast, fuel-specific heavy trucks (gasoline), port drayage, and recreational/pleasure vehicle groups experienced VMT declines of -32%, -3%, and -54%, respectively, over the same period.

Overall, the top five vehicle groups account for 98.1% of total VMT, while the remaining eight groups account for only 1.9%. A distinct V-shaped dip appears across nearly all vehicle groups around 2020, confirming the widespread impact of pandemic-related restrictions. While daily commute & household VMT recovers to near pre-pandemic levels, out-of-state freight activity is projected to increase, exceeding 2019 levels by approximately 38% by 2032.

Figure 4. Emission Trends by Fuel Type in Fresno County (2000–2032), EMFAC 2025 Model



Emission Trends by Fuel Types

Figure 4 shows time-series emissions of six major pollutants, PM_{2.5}, PM₁₀, NO_x, SO_x, CO₂, and CO, by fuel type in Fresno County over the 2000–2032 period. Each panel visualizes total emissions trends by calendar year, highlighting how different fuel sources contribute to air pollution and how these contributions are projected to change.

Emissions from Diesel Fuel Vehicles

Diesel fuel contributed to PM_{2.5}, PM₁₀, NO_x, and SO_x throughout the early 2000s. Emissions show a steep and consistent decline for all air pollutants between 2000 and 2030, mainly due to stricter emissions standards, such as the Tier-4 standard, low-sulfur diesel regulations, and the adoption of cleaner diesel technologies. In the early 2000s, diesel vehicles were the primary source of particulate matter, emitting approximately 1.6-1.8 tons/day. However, a dramatic reduction is observed starting around 2008, with diesel emissions plummeting to near 0.2 tons/day after 2022 (88%).

Diesel vehicles were historically the largest contributors to NO_x, reaching nearly 50 tons/day in the early 2000s. This has decreased consistently, converging with gasoline emissions near zero by 2032 (98%). The SO_x trend reveals a distinct cliff around 2006, where diesel emissions dropped sharply from 0.38 tons/day to near zero (~100%). This sudden shift corresponds with the introduction of Ultra-Low Sulfur Diesel (ULSD) regulations.

Diesel contributions to Carbon Monoxide (CO) are negligible throughout the entire time period. Diesel CO₂ emissions have remained relatively flat, averaging around 4,000 tons/day, indicating that while diesel engines have become cleaner for PM, NO_x, and SO_x, their fuel consumption and CO₂ production have remained steady.

Emissions from Gasoline Fuel Vehicles

Gasoline fuel emissions are the major sources of CO and CO₂. CO emissions decreased steadily (by 67%) over the time series, reflecting engine efficiency gains and emissions controls (e.g., catalytic converters). CO₂ shows a modest decline starting around 2018, indicating slight decarbonization, but continued gasoline use in light-duty vehicles and their high volume increases total VMT. Unlike other air pollutants, CO₂ is the greenhouse gas that does not show a dramatic long-term reduction to near-zero levels. Gasoline vehicles remain the dominant source, fluctuating between 7,500 and 9,000 tons/day. CO₂ shows the least progress in reducing emissions over the 32 years.

In contrast to diesel engines, gasoline engines' PM_{2.5} and PM₁₀ emissions have remained relatively low and stable throughout the period, hovering below 0.3 tons/day. Gasoline vehicles also show a steady decline in NO_x emissions from roughly 22 tons/day to negligible levels (95%). The SO_x trend reveals a distinct cliff around 2002, where diesel emissions dropped sharply from 0.1 tons/day to around 0.03 tons/day (near zero). Notably, SO_x emissions from gasoline have been higher than those from diesel since 2006.

Alternative Fuels

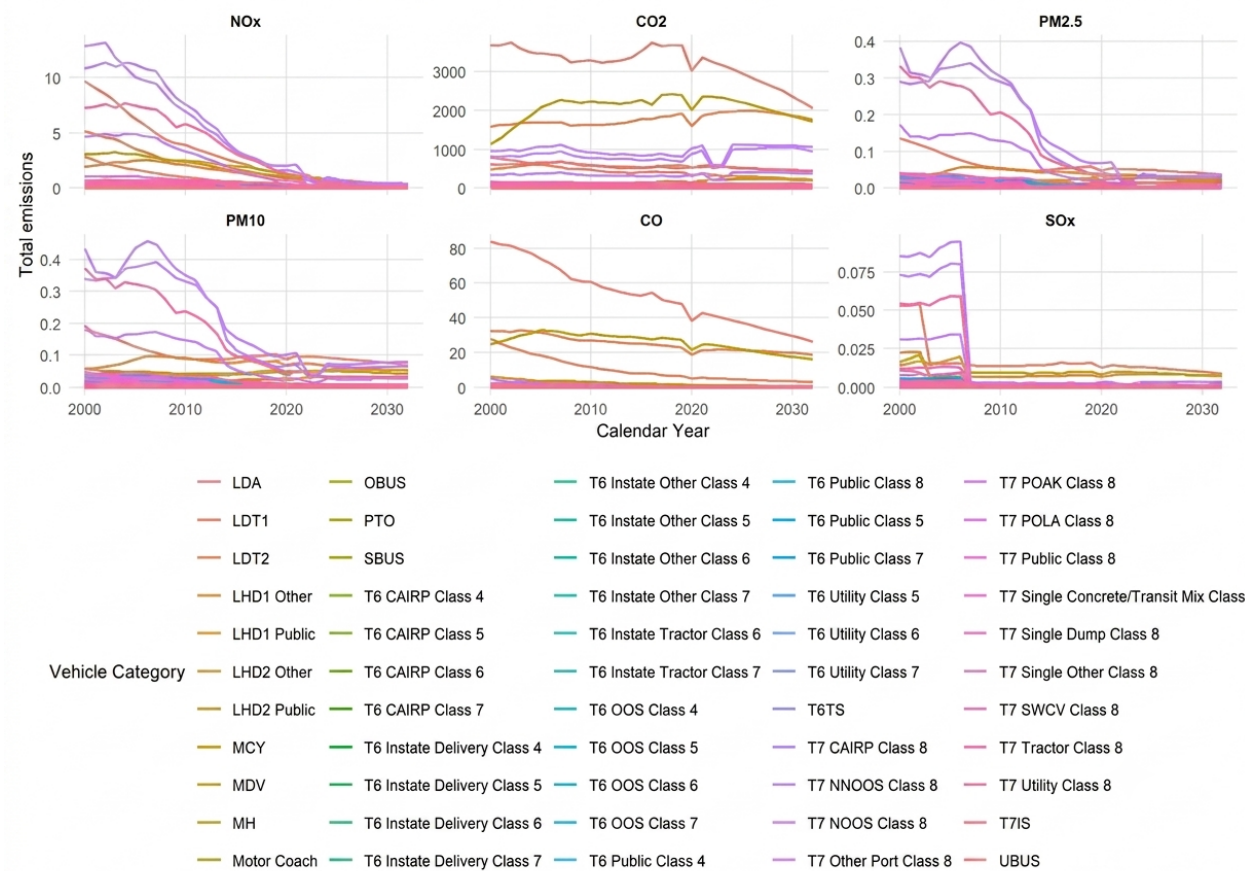
Electric, Natural Gas, Fuel Cell, and Plug-in Hybrid fuel types appear as flat lines (near zero) on these scales, indicating they currently account for a minor fraction of total mass emissions in this inventory compared to conventional fossil fuels.

The EMFAC model projects substantial progress in reducing tailpipe emissions from diesel and gasoline vehicles due to technological and regulatory interventions. However, CO₂ remains a persistent challenge, with deep reductions dependent on the wider adoption of electric and zero-emission vehicles. Overall, the data support continued investment in clean vehicle technologies and stringent emissions standards to meet air quality and climate goals.

Emission Trends by Vehicle Categories

Emissions from most vehicle categories in Fresno County show a consistent downward trend from 2000 to 2032 for all criteria pollutants emitted by mobile sources, except CO₂, with slight declines in some categories (Figure 5). As a greenhouse gas and a primary product of the complete combustion of carbon-based fuels, CO₂ emissions are stable across most vehicle categories and have recently shown slight declines in light-duty gasoline-engine vehicles. The stable CO₂ emissions trends reflect that aggregate fuel consumption has not decreased significantly, as evidenced by VMT growth. Emissions of photochemical precursors and smog-forming pollutants, such as NO_x, SO_x, PM_{2.5}, PM₁₀, and CO, declined by 67% to 99% across almost all vehicle categories.

Figure 5. Emission Trends by Vehicle Category in Fresno County (2000–2032)
EMFAC 2025 Model



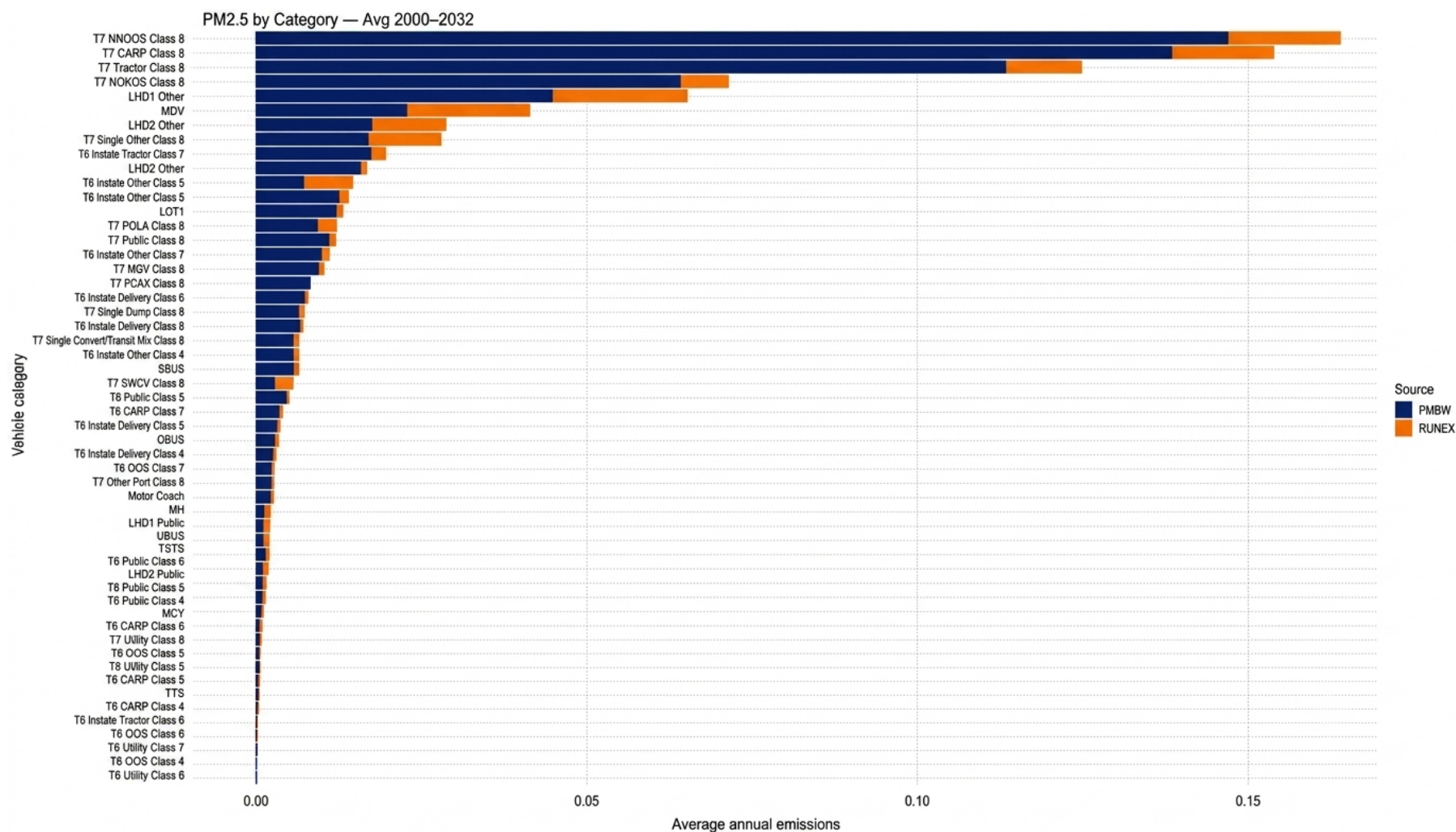
Heavy-duty diesel vehicles (e.g., tractors, Class 8 trucks) initially contributed the most. Still, they declined significantly after 2015 due to cleaner engine technologies and stricter fuel regulations, such as the adoption of ultra-low-sulfur diesel. Light-duty vehicles also show steady reductions in emissions over time. While engines burn fuel far more cleanly, producing less smog-forming pollutants, the total amount of fuel burned has not dropped significantly because vehicle miles traveled (VMT) continue to rise, offsetting efficiency gains. These trends show that cleaner engines and fuel technologies have successfully reduced toxic air pollutants and decoupled them from economic activity and growth. However, carbon emissions have not yet decoupled from travel demand and greenhouse gases.

The Shift of Sources: From Exhaust to Frictions

Historically, exhaust emissions (RUNEX, teal bars) were the primary source of particulate matter. However, as engine regulations tightened, exhaust emissions steadily declined, leaving brake wear particles (PMBW, red bars) as the dominant source of particulate matter (PM₁₀ and PM_{2.5}) by 2017 and 2023, respectively (Figures 7 & 9). Total emissions show a steady decline from 2000 to around 2020, driven by successful reductions in particulate matter emissions. After 2020, the

trend becomes stable because brake wear, which is tied to miles driven rather than engine technology, remains constant or increases slightly with traffic volume. The largest contributors to these emissions are heavy-duty interstate trucks (Class 8) and standard passenger cars (LDA). While trucks historically contributed heavily to exhaust emissions, passenger cars are a major source of brake and tire wear due to their high daily travel volume (Figures 6–9).

Figure 6. Average Annual PM_{2.5} Emissions by Vehicle Category (2000–2032)
Running Exhaust Emissions (RUNEX) Brake Wear Particulate Matter Emissions (PMBW)



The coarse, heavier particulate matter, consisting of PM₁₀ from mechanically produced brake dust pollution, became a larger fraction in 2017 as exhaust emissions were significantly reduced. PM_{2.5} from brake wear becomes a larger portion than exhaust in 2023, a few years after PM₁₀. This crossover in particle-emission sources marks a fundamental change in air-quality management. For decades, policy focused on engine combustion (cleaner fuels, better filters).

Figure 7. PM_{2.5} Emission Composition Over Time (2000–2032)
Running Exhaust Emissions (RUNEX) Brake Wear Particulate Matter Emissions (PMBW)

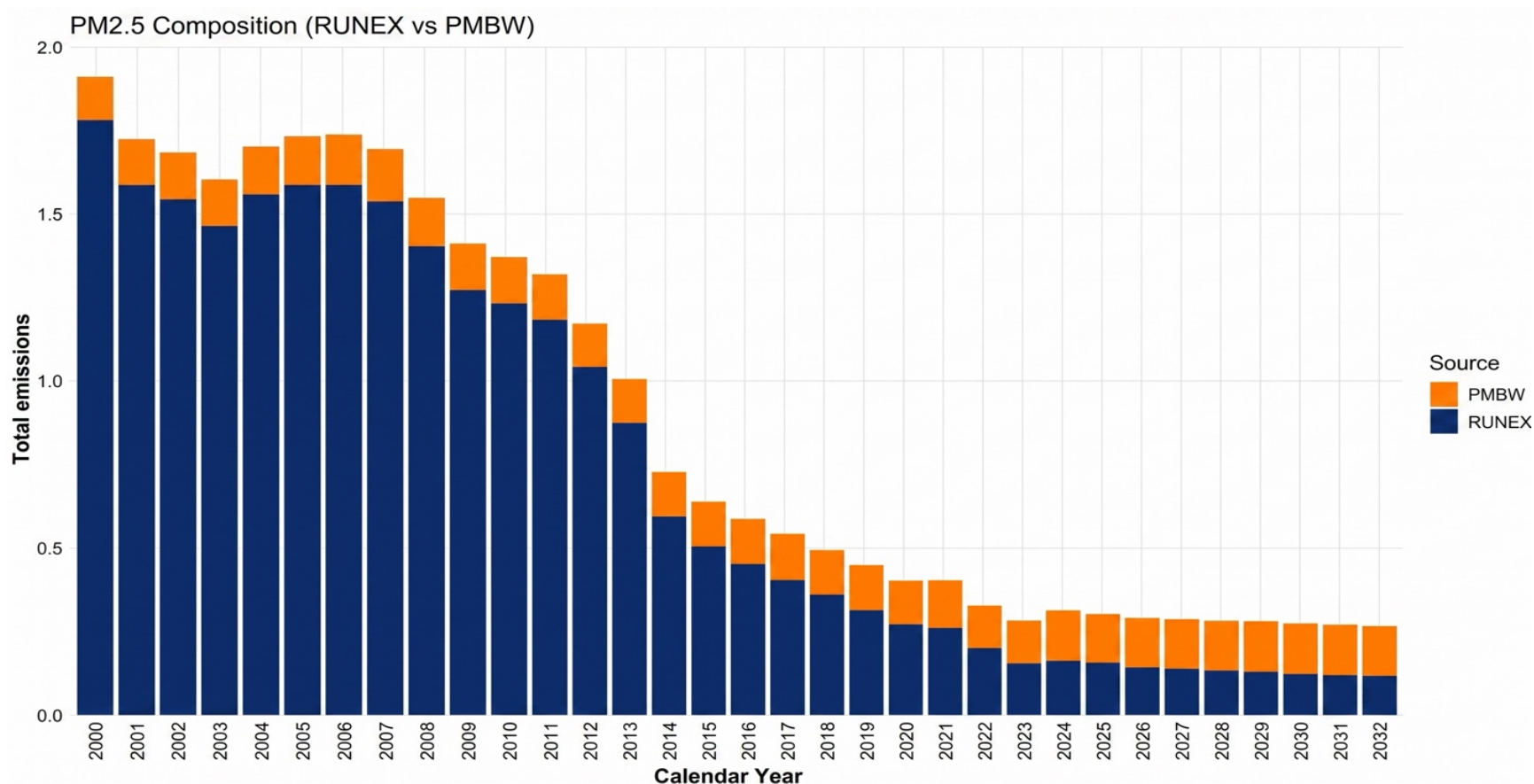


Figure 8. Average Annual PM₁₀ Emissions by Vehicle Category (2000–2032)
Running Exhaust Emissions (RUNEX) Brake Wear Particulate Matter Emissions (PMBW)

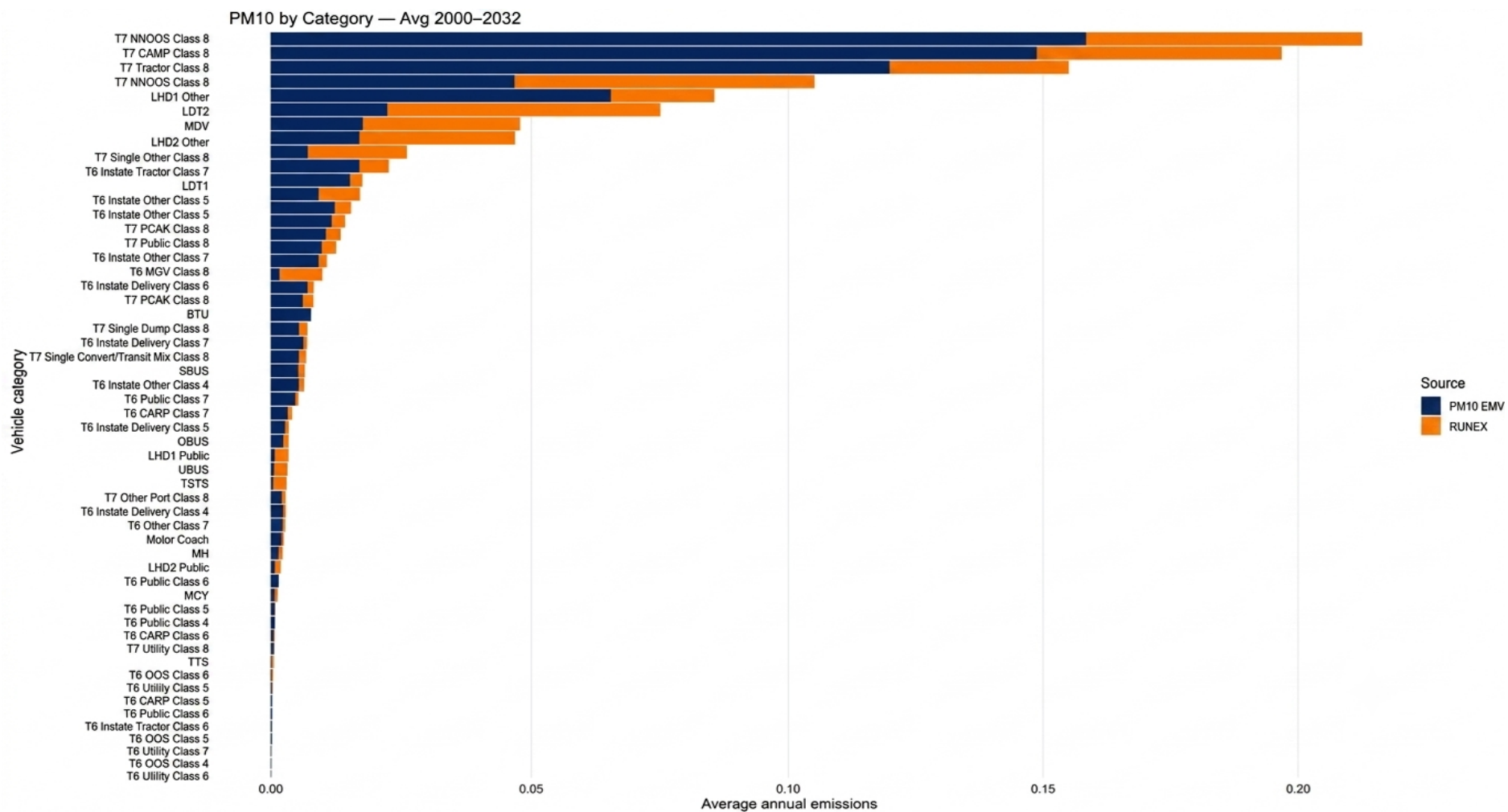
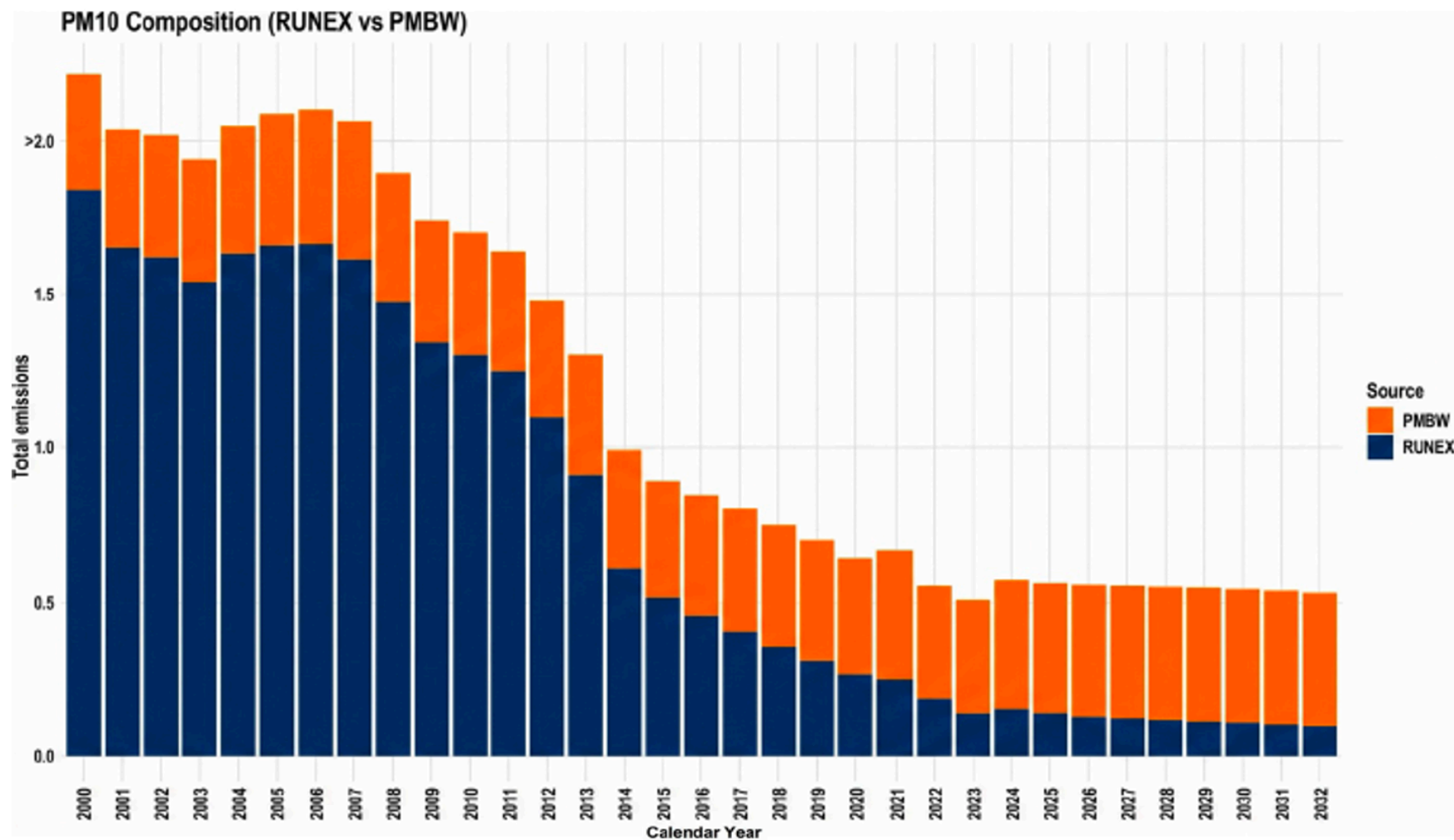


Figure 9. PM₁₀ Emission Composition Over Time (2000–2032)
Running Exhaust Emissions (RUNEX) Brake Wear Particulate Matter Emissions (PMBW)



Now, the primary source of particle pollution is vehicle weight and friction. Because electric vehicles (EVs) are often heavier than gas cars due to their batteries, they still generate significant brake and tire wear, meaning a switch to zero-emission engines solves the exhaust problem but not the wear problem.

PM_{2.5} On-Road Mobile Sources Emissions in Fresno County (2000–2032)

Annual average daily PM_{2.5} emissions from on-road mobile sources in Fresno County have declined significantly and consistently from 2000 to 2032 (Figure 10). In the early 2000s, total PM_{2.5} from mobile source emissions exceeded 1.5 tons per day, but by 2032, this total is projected to fall below 0.3 tons per day. This reduction was not uniform across all vehicles. The chart shows that the large wedges representing commercial freight, specifically out-of-state trucks (purple), in-state tractors (red), and interstate fleets (light blue), shrank disproportionately quickly. In the early 2000s, these heavy-duty trucks accounted for a large share of the emissions inventory. By the end of the period, their contribution had become a thin sliver, leaving a much smaller overall inventory, in which passenger vehicles (the black bar) now account for a larger visual share, simply because emissions from other categories disappeared. The reduction is largely driven by tighter emissions standards, cleaner technologies, and fleet turnover across multiple vehicle categories.

In Figure 11, trend lines for umbrella vehicle categories illustrate the declining trajectory across all sources. While Figure 11 shows that total emissions dropped, the primary source of PM_{2.5} shifted around 2018 from historical heavy-duty diesel trucks to gasoline-powered passenger cars for commuting and household use (black line), marking a major turning point in air quality history. Aggressive California regulations, such as the Truck and Bus Rule and Clean Truck Check, contributed to a massive reduction in PM_{2.5} from on-road mobile emissions, bringing levels to near-zero by 2032. In contrast, the daily commute & household category (black line) remained relatively stable. While cars became cleaner, the sheer volume of daily traffic kept their aggregate emissions consistent. The diesel problem has largely been solved, leaving volume of traffic as the new challenge in air quality associated with mobile sources on the road.

Figure 10. Annual Average Daily PM_{2.5} Emissions by Vehicle Category in Fresno County

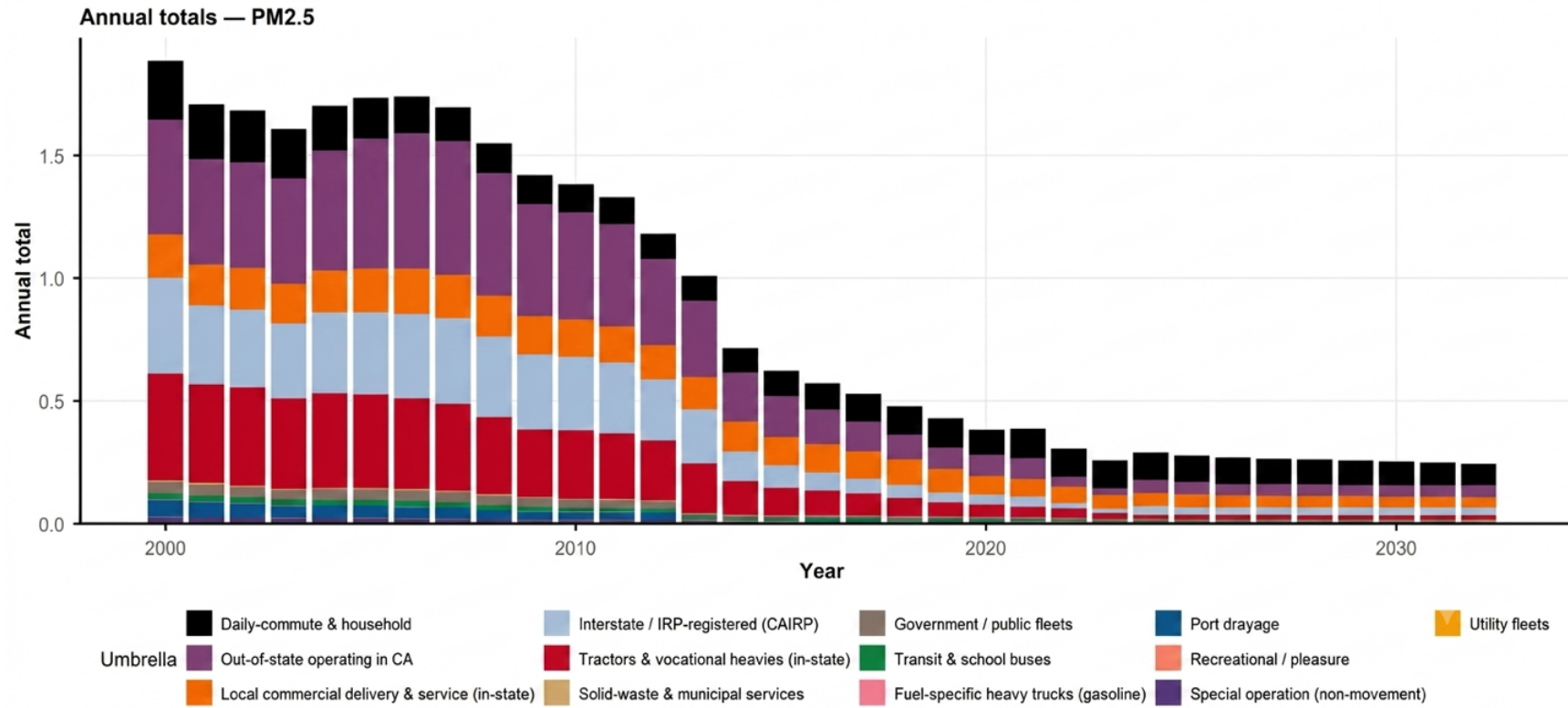


Figure 11. PM_{2.5} Emissions Trends by Vehicle Category in Fresno County
(2000–2032)

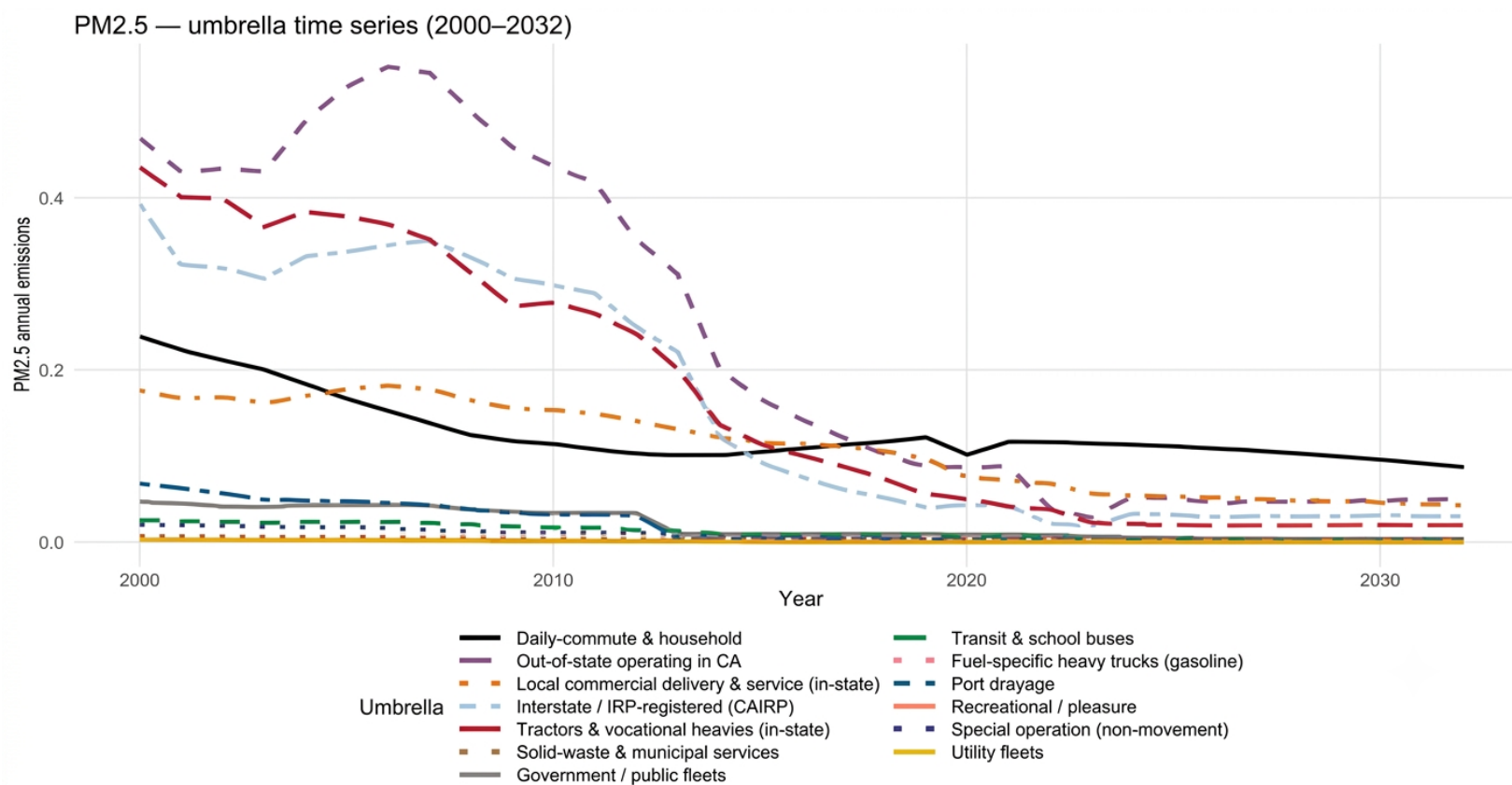
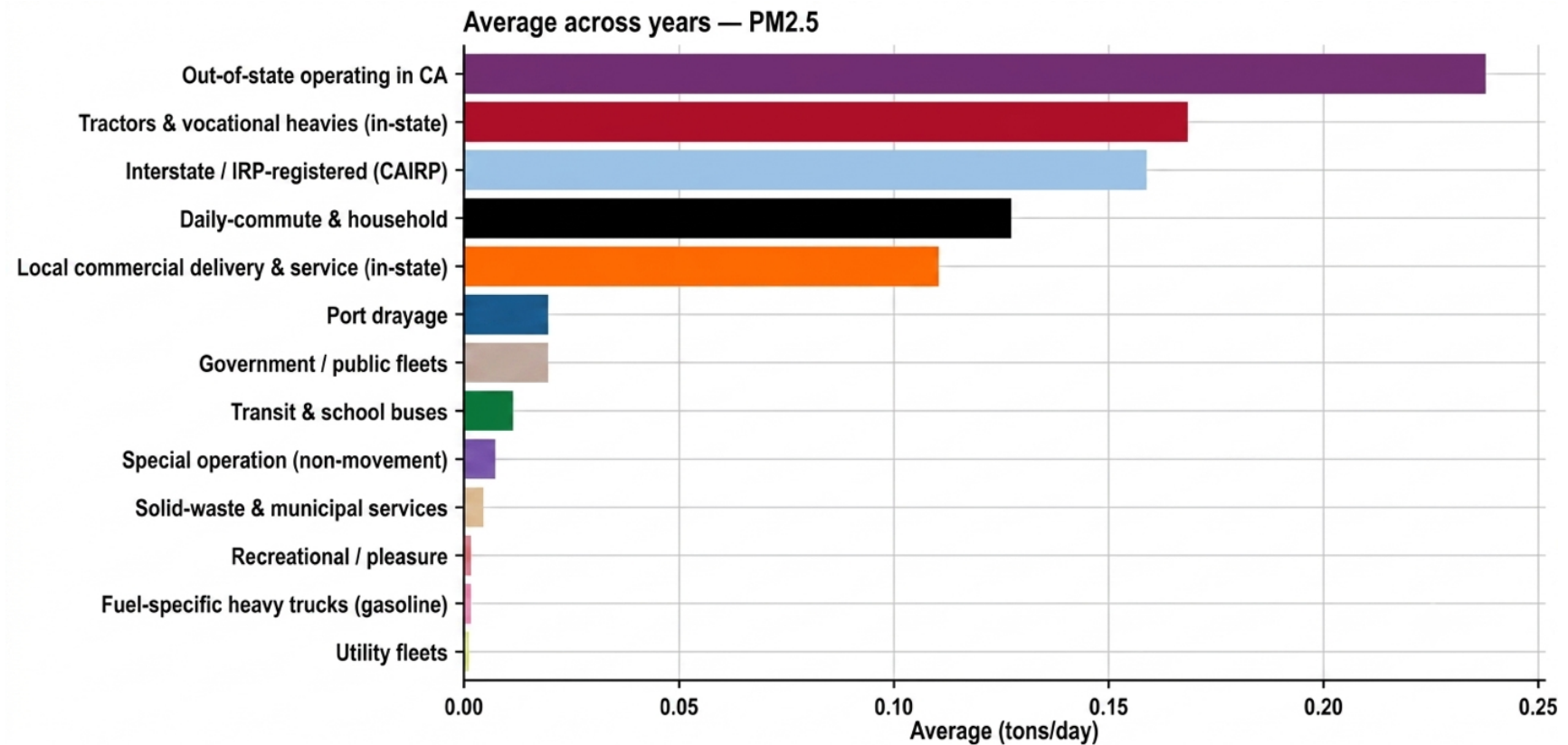


Figure 12. Contribution to PM_{2.5} Emissions by Vehicle Category
(Averages Across 2000–2032)



Despite the recent success in cleaning up trucks, Figure 12 ranks historical PM_{2.5} contributions by vehicle category. When averaging emissions over the entire 32-year period, heavy-duty freight remains the dominant contributor. Out-of-state trucks were the largest contributors to PM_{2.5} emissions, followed by in-state tractors & vocational trucks and IRP-registered interstate fleets. These top three categories together account for a majority of PM_{2.5} emissions, underscoring the outsized impact of heavy-duty freight movement. In contrast, groups such as utility fleets, fuel-specific heavy trucks, and recreational/pleasure vehicles contributed negligible amounts to total emissions. Even though passenger cars are the current leader, as shown in the trend line, the massive historical pollution from diesel trucks means that, on average, the freight sector was responsible for the majority of the particulate matter burden Fresno County faced over the last three decades. The combined evidence from annual average daily PM_{2.5}, temporal trends from 2000 to 2032, and 21-year average contributions highlights a clear shift in emissions. While overall PM_{2.5} is declining, freight-related categories continue to dominate the remaining inventory. This suggests that future mitigation efforts should continue to prioritize long-haul and in-state heavy-duty truck activity for continued air quality improvement.

PM₁₀ On-Road Mobile Source Emissions in Fresno County (2000–2032)

Annual average daily PM₁₀ emissions from on-road mobile sources in Fresno County have also declined significantly from 2000 to 2032 (Figure 13). In the early 2000s, PM₁₀ emissions exceeded 2.0 tons per day, but by 2032, total daily emissions are projected to fall below 0.5 tons per day. This decline is largely due to emissions-control policies, cleaner engine technologies, and fleet modernization. Unlike PM_{2.5}, however, passenger cars (black bar) were already a substantial contributor at the beginning of the period and remained a major source throughout the period. Emissions from out-of-state trucks, in-state tractors, and interstate (IRP) fleets also declined sharply over time, though not as disproportionately as with PM_{2.5}.

In Figure 14, the trend lines show that passenger vehicles used for commuting and household purposes (black line) consistently remained among the top sources of PM₁₀ throughout the entire period. This is a distinct difference from PM_{2.5}, where their share only rose in later years. While heavy-duty trucks, including out-of-state, in-state vocational, and IRP-registered fleets, still saw steep declines, passenger vehicle emissions did not diminish as sharply, surpassing freight categories by approximately 2015–2017. This shift highlights a fundamental change in the nature of pollution: As regulations such as the Truck and Bus Rule successfully eliminated tailpipe exhaust, the primary driver of coarse particulate matter shifted to mechanical wear (brake and tire dust). Since passenger cars account for over 80% of the daily traffic volume, they naturally generate the highest volume of friction-based pollution, keeping their aggregate PM₁₀ emissions relatively stable even as their engines become cleaner.

Figure 13. Annual Average Daily PM₁₀ Emissions by Vehicle Category in Fresno County

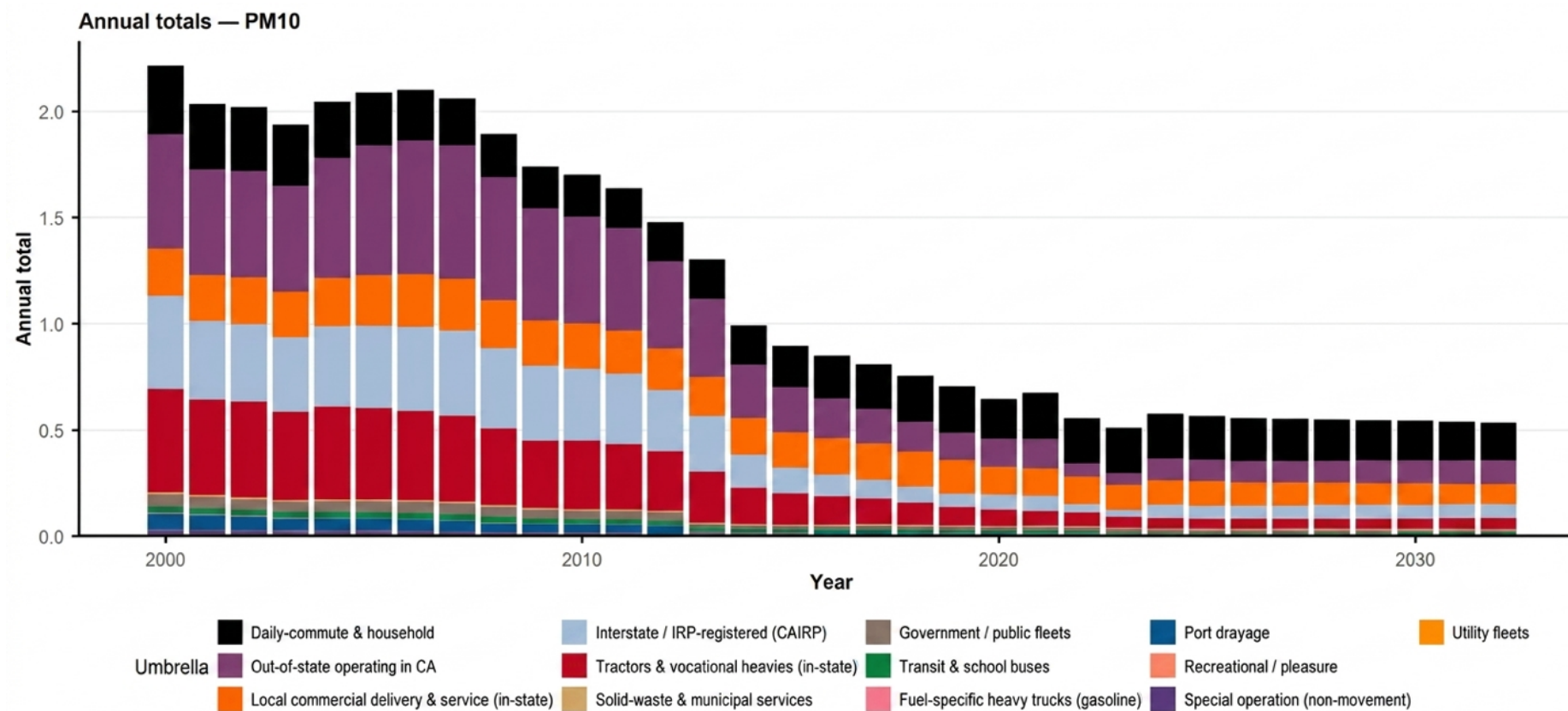


Figure 14. PM₁₀ Emissions Trends by Vehicle Category in Fresno County (2000–2032)

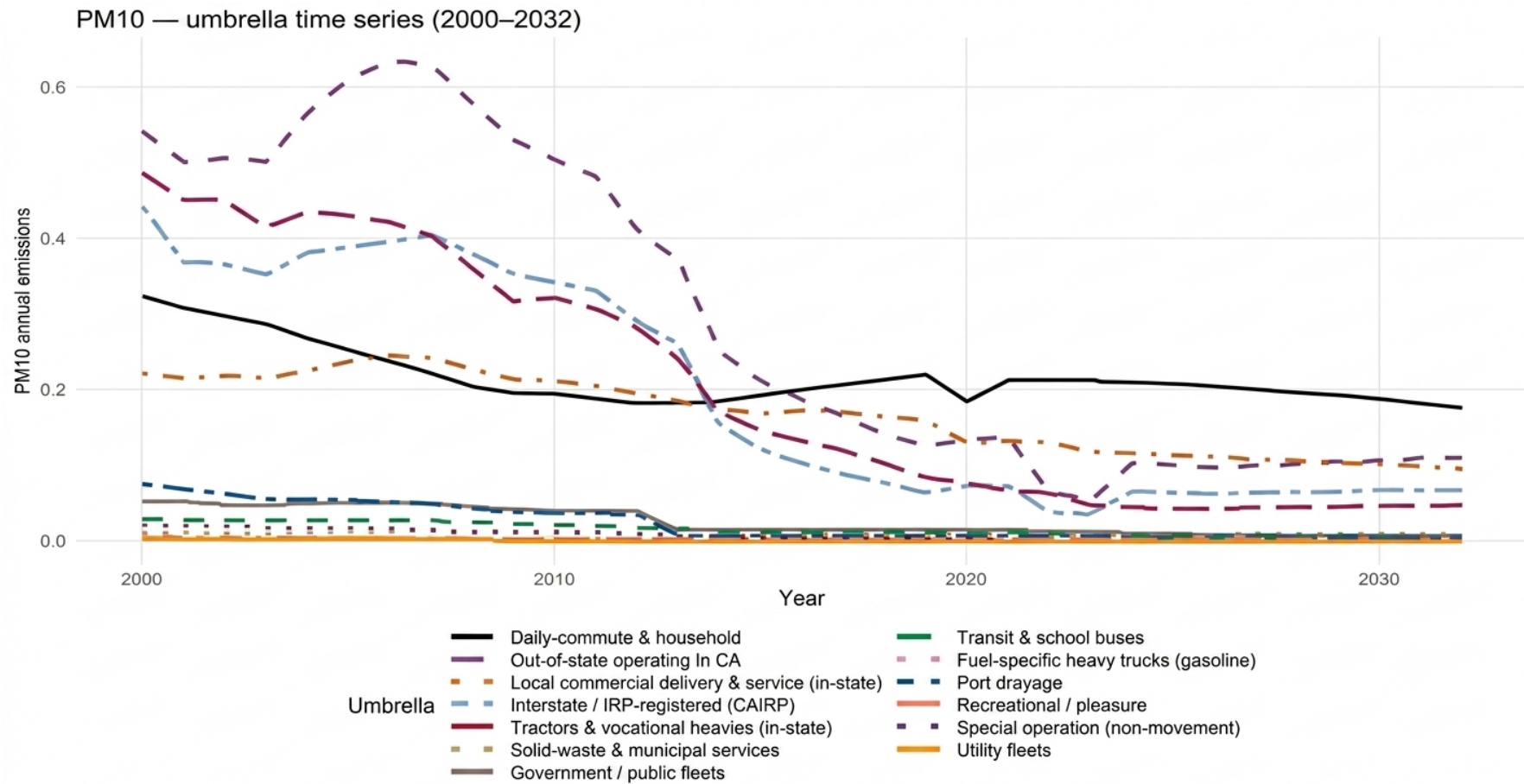


Figure 15. Contribution to PM₁₀ Emissions by Vehicle Category (Averages Across 2000–2032)

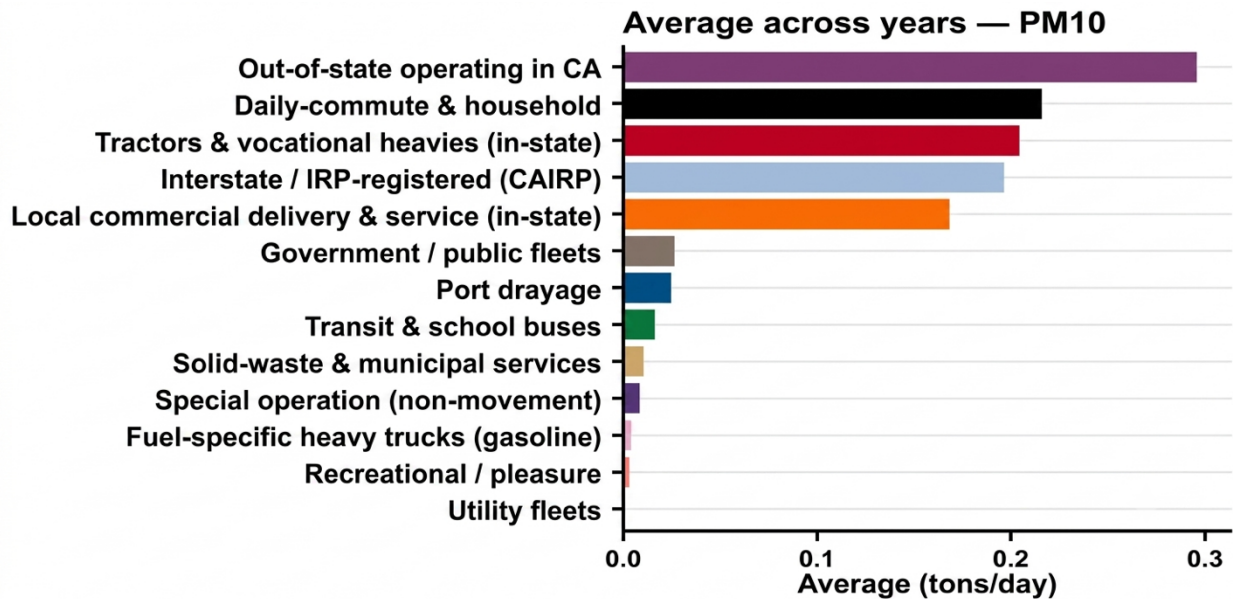


Figure 15 provides the historical average ranking of contributors to PM₁₀ emissions from 2000 to 2032. Interestingly, out-of-state diesel trucks remain the top contributor, followed closely by daily-commute & household gasoline vehicles, ranked second, unlike in PM_{2.5}, where they were fourth. In-state tractors, IRP fleets, and local commercial delivery & service complete the top five contributors. These shifts highlight the unique role of light-duty vehicles in PM₁₀ emissions, particularly through non-exhaust sources such as resuspended road dust and tire/brake wear, which are more prominent in the PM₁₀ size range.

The combined evidence from Figures 13–15 shows that, while PM₁₀ emissions have been significantly reduced, the dominant contributors differ from those for PM_{2.5}. Passenger vehicles remain a major PM₁₀ source throughout, unlike the freight-dominated PM_{2.5} profile. While total PM₁₀ has declined, the projected inventory remains high and is tied to vehicle movement rather than combustion efficiency. This suggests that future improvements in PM₁₀ air quality will be more difficult to achieve solely through engine standards. In addition to continued controls on heavy-duty diesel exhaust, policies may require strategies to reduce overall vehicle miles traveled, promote mode shift, or manage vehicle weight.

NO_x On-Road Mobile Source Emissions in Fresno County (2000–2032)

Annual average daily NO_x emissions from on-road mobile sources in Fresno County show a dramatic and continuous decline over the 2000–2032 period (Figure 16). In the early 2000s, total NO_x emissions from mobile sources exceeded 80 tons per day, but by 2032, they are projected to fall below 10 tons per day. This steep reduction was driven by the phase-in of low-NO_x engines, diesel retrofit programs, and California’s stringent emissions regulations. The sharpest decreases are visible in major freight categories, interstate (IRP) fleets, out-of-state trucks, and in-state

tractors & vocational vehicles, which were responsible for the major portion of early emissions but have since been heavily mitigated. The emission bars representing these categories have narrowed significantly, reflecting real-world progress in controlling heavy-duty diesel emissions.

In Figure 17, the category-specific trend lines further illustrate this downward shift across all vehicle groups. Unlike $PM_{2.5}$ and PM_{10} , the daily-commute & household group (black line) consistently contributes the most NO_x emissions throughout the period. While heavy-duty freight vehicles (purple, red, and light blue lines) still show high emissions in early years, their steep decline is evident after 2010. Conversely, emissions from light-duty gasoline-powered vehicles have declined more gradually due to higher traffic volumes and lower per-vehicle NO_x control stringency than those from diesel engines. By the 2020s, NO_x emissions from passenger cars surpassed those from most freight groups, reflecting both their slower emissions decline and the sheer number of vehicles. This inversion marks a major shift in the source profile of NO_x pollution.

Despite the recent dominance of light-duty vehicles, Figure 18 shows that, over the entire 32-year period, passenger vehicles (daily commute & household) are the largest cumulative contributors to NO_x emissions. This contrasts with $PM_{2.5}$ and PM_{10} , where heavy-duty diesel trucks have historically dominated the burden. Out-of-state trucks, IRP-registered fleets, and in-state vocational trucks still rank highly but are secondary contributors to the overall NO_x burden. This shift highlights the greater contribution of gasoline engines to NO_x compared to particulate matter, particularly when considering cumulative emissions over multiple decades. Other categories, such as utility fleets, fuel-specific heavy trucks, and recreational vehicles, remain negligible contributors throughout due to low VMTs.

Figure 16. Annual Average Daily NO_x Emissions by Vehicle Category in Fresno County

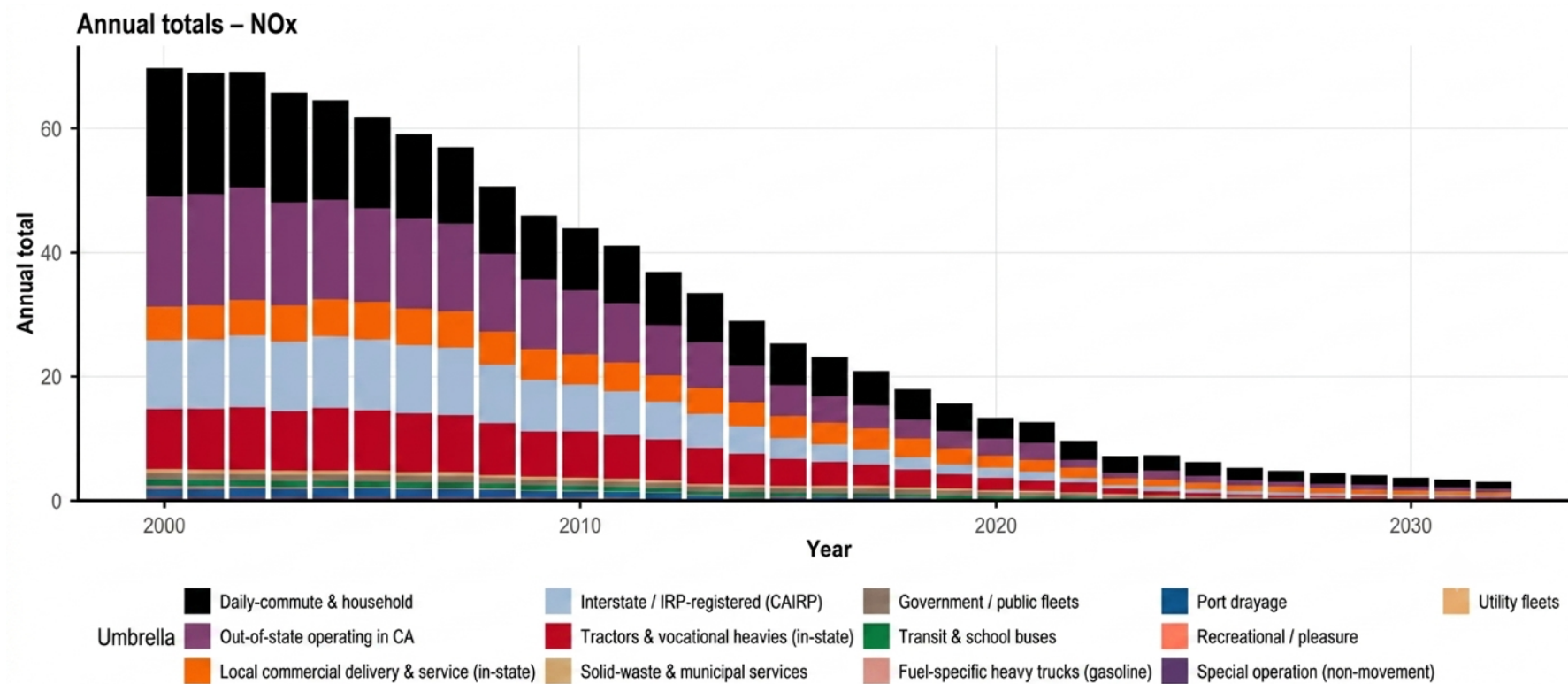


Figure 17. NO_x Emissions Trends by Vehicle Category in Fresno County (2000–2032)

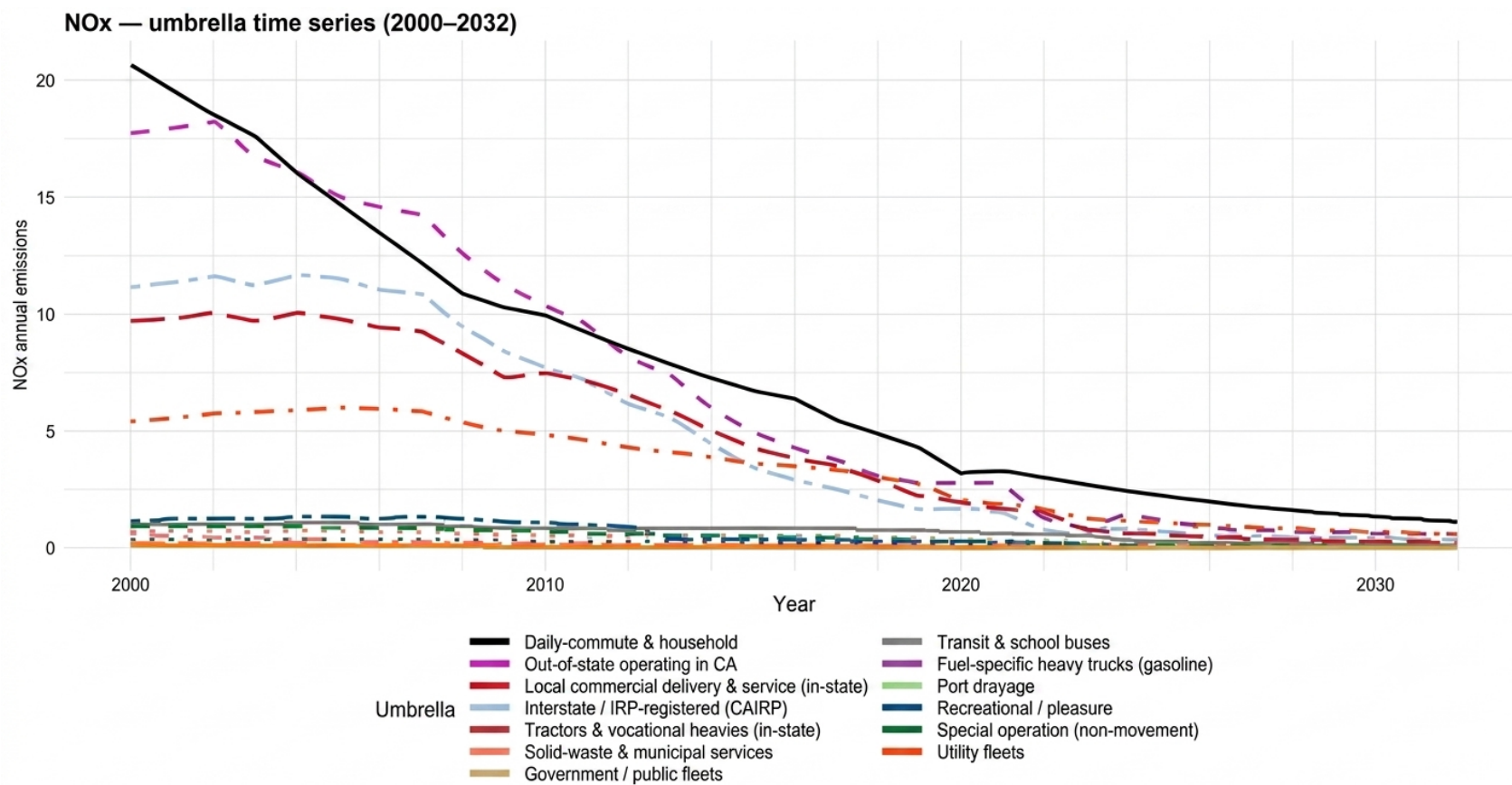
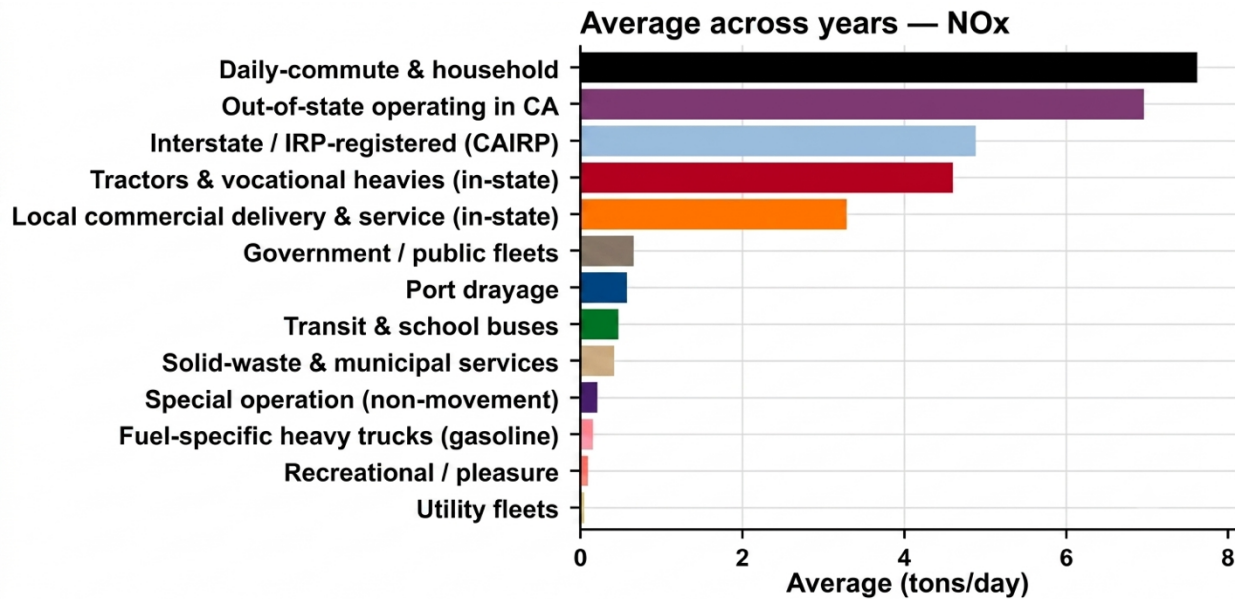


Figure 18. Contribution to NO_x Emissions by Vehicle Category (Averages Across 2000–2032)



Together, Figures 16, 17, and 18 illustrate a compelling story of regulatory success and evolving challenges. While emissions from freight vehicles have been significantly reduced, light-duty vehicles remain a persistent source of NO_x in the emissions inventory. Continued reductions in NO_x will likely depend on reducing passenger-vehicle activity, accelerating fleet electrification, and targeting the remaining high-emission subsets in both light- and heavy-duty classes.

SO_x On-Road Mobile Source Emissions in Fresno County (2000–2032)

Annual average daily sulfur oxide (SO_x) emissions from on-road mobile sources in Fresno County experienced a dramatic and abrupt reduction around 2006, as shown in Figure 19. In the early 2000s, total SO_x emissions exceeded 0.4 tons per day, but by 2007, emissions dropped sharply to below 0.05 tons/day, where they have remained at near-zero flat levels through 2032. This reduction was overwhelmingly driven by the introduction of ultra-low sulfur diesel (ULSD) regulations, which mandated near-zero sulfur content in fuels, eliminating refinery-level sulfur used by on-road diesel vehicles. The previously dominant SO_x emitters, including out-of-state trucks (purple), in-state tractors (red), and IRP-registered fleets (light blue), show substantial emission wedges before 2006 that virtually disappear afterward. Meanwhile, the daily commute & household category (black line) continues to show a stable presence before and after the drop, making up the largest share of the post-ULSD emissions profile.

Figure 20 further illustrates this trend, with sharp breaks in the time-series lines around 2006 across nearly all categories. Emissions from freight-related diesel categories plummet to near-zero, while the daily-commute & household group (black line) remains relatively flat throughout the time period. This trend reflects the unique nature of SO_x emissions: They are highly fuel-dependent rather than driven by engine combustion conditions or technology. Once

sulfur levels in fuel were dramatically reduced by policy, SO_x emissions followed almost immediately. Unlike PM and NO_x, there was no gradual decline, but only a swift, sustained drop. The data indicate that the sulfur problem in on-road mobile sources has been effectively solved through fuel reformulation. However, because gasoline-powered vehicles still contain trace amounts of sulfur, light-duty passenger vehicles remain the largest source of residual SO_x.

Despite freight categories driving the early-2000s SO_x burden, Figure 21 shows that over the full 2000–2032 period, daily-commute & household vehicles are the largest average contributors to SO_x emissions. Out-of-state trucks and IRP fleets follow closely behind, reflecting their high impact before 2006. In-state tractors and local commercial delivery fleets also appear in the top five contributors, but with significantly lower average levels. The remaining categories, including utility fleets, recreational vehicles, and fuel-specific trucks, contributed only minor amounts throughout the study period.

Overall, these figures confirm that SO_x emissions have been successfully and almost entirely mitigated through fuel sulfur regulations, particularly those targeting diesel. While freight vehicles were historically significant contributors, their emissions dropped so abruptly that light-duty passenger vehicles now constitute the main residual source. The focus for future SO_x reduction may shift toward gasoline fuel refining and further desulfurization if even lower residual levels are to be achieved.

Figure 19. Annual Average Daily SO_x Emissions by Vehicle Category in Fresno County

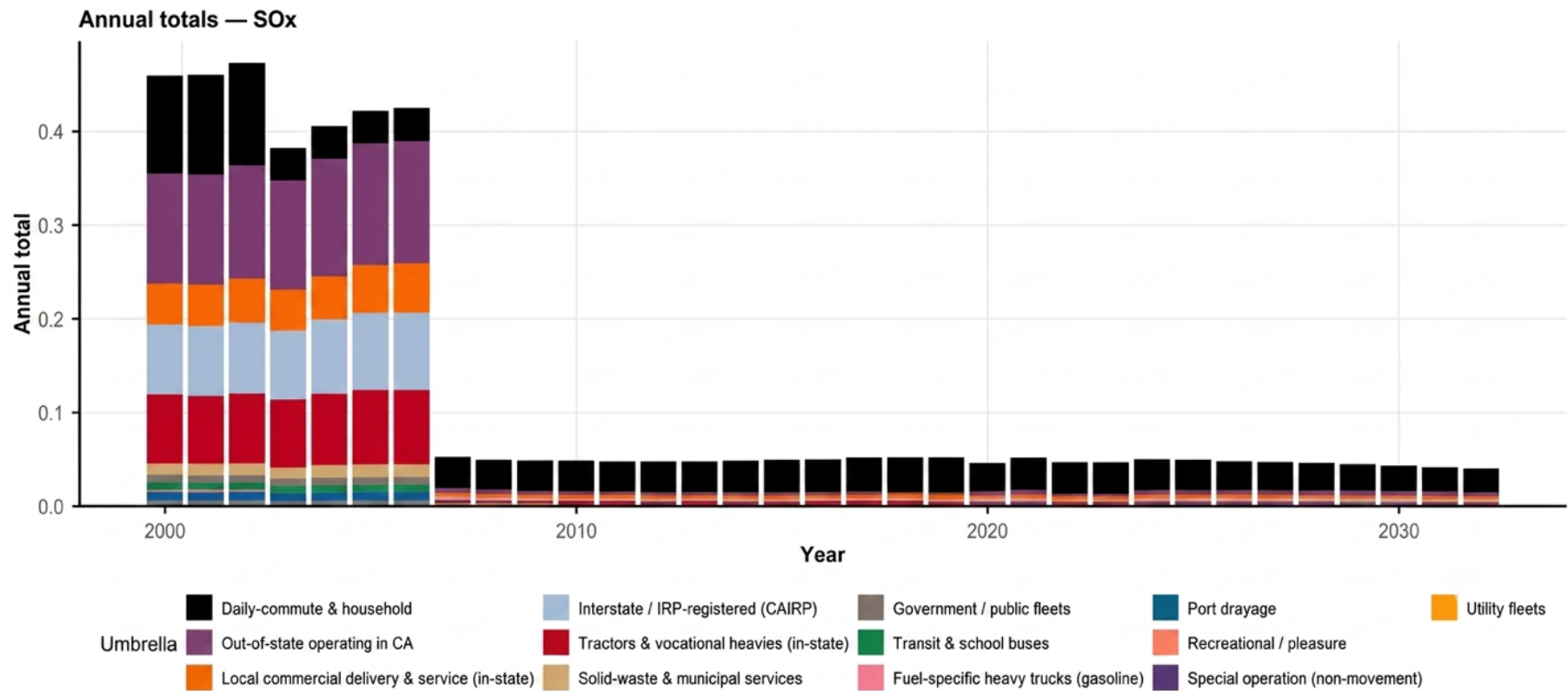


Figure 20. SO_x Emissions Trends by Vehicle Category in Fresno County (2000–2032)

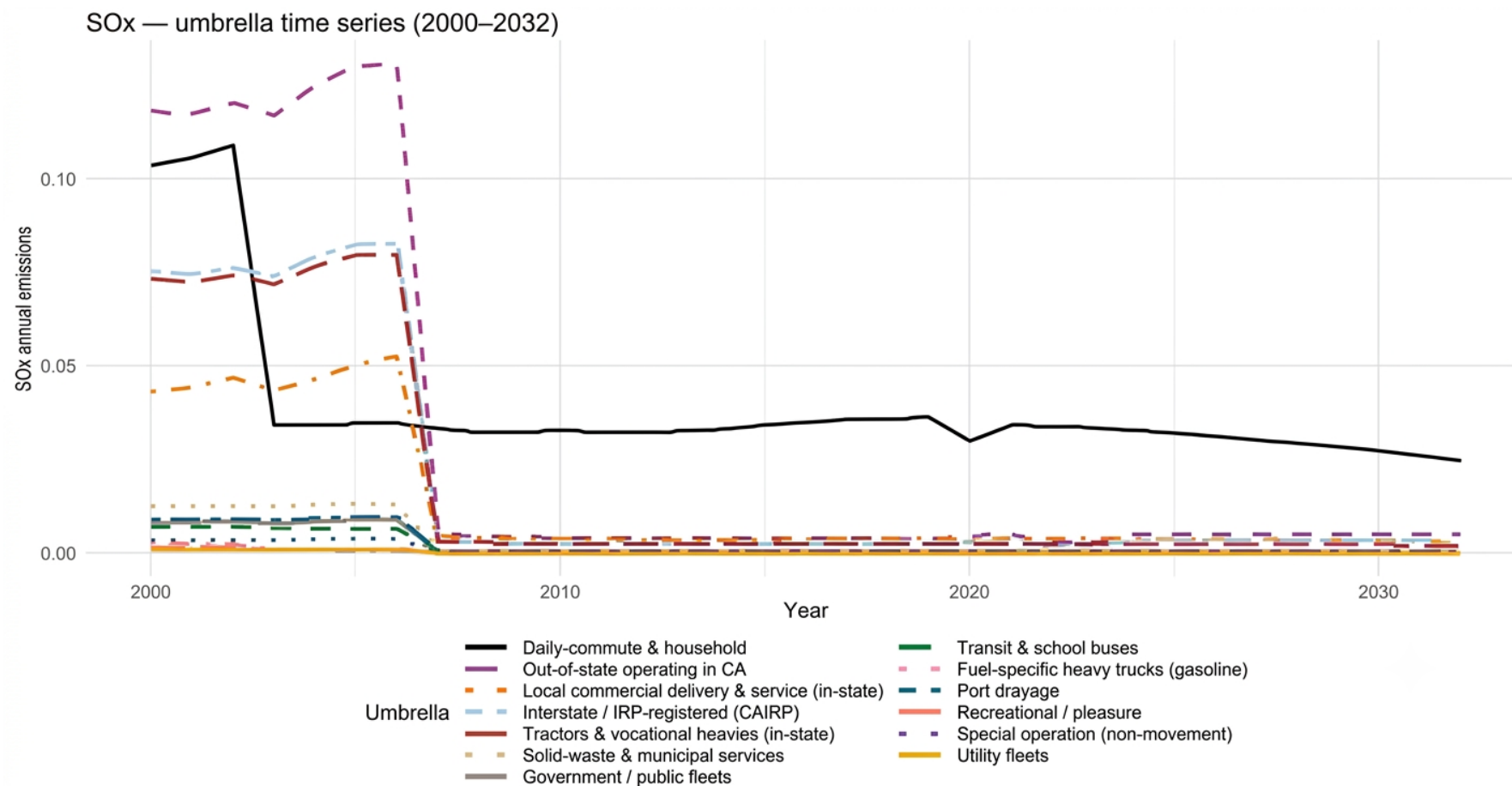


Figure 21. Contribution to SO_x Emissions by Vehicle Category (Averages Across 2000–2032)

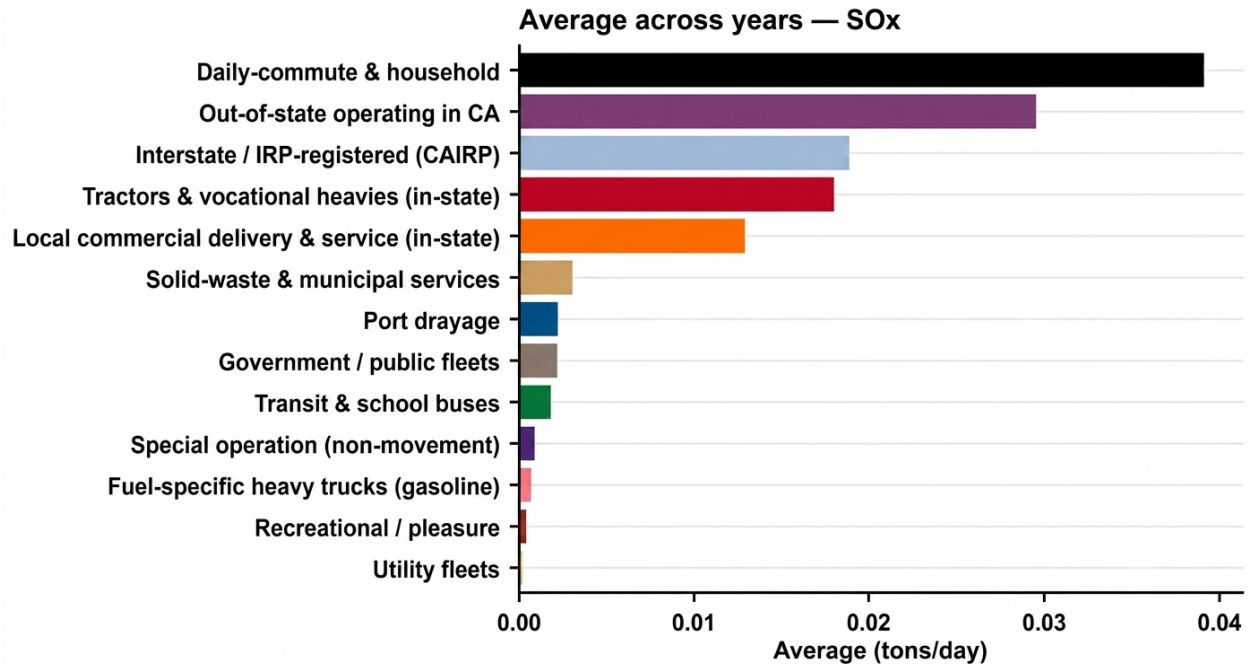


Figure 22. Annual Average Daily CO Emissions by Vehicle Category in Fresno County

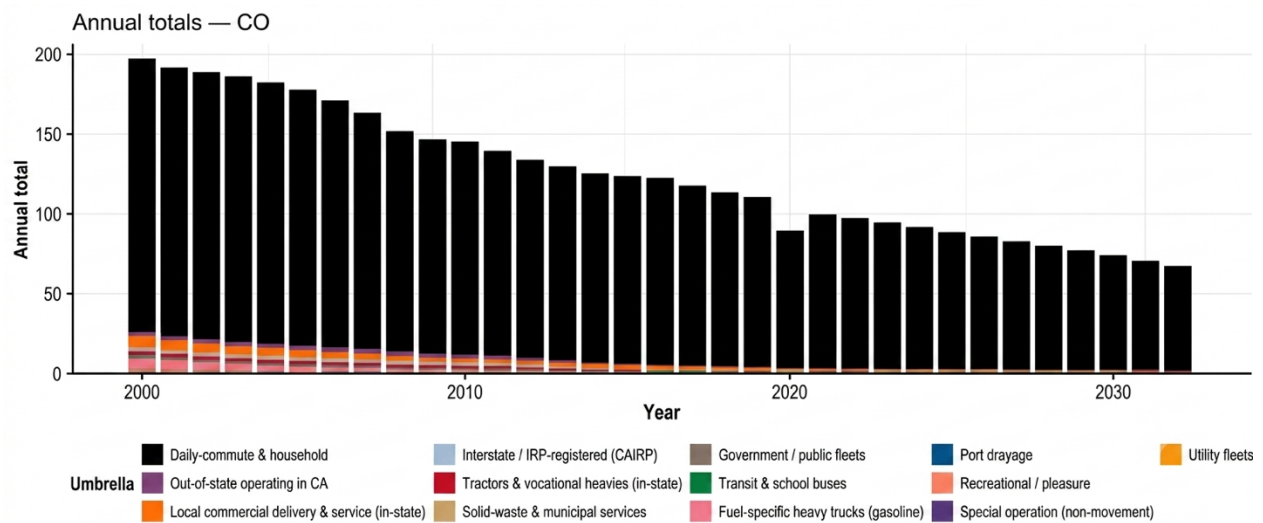


Figure 23. CO Emissions Trends by Vehicle Category in Fresno County (2000–2032)

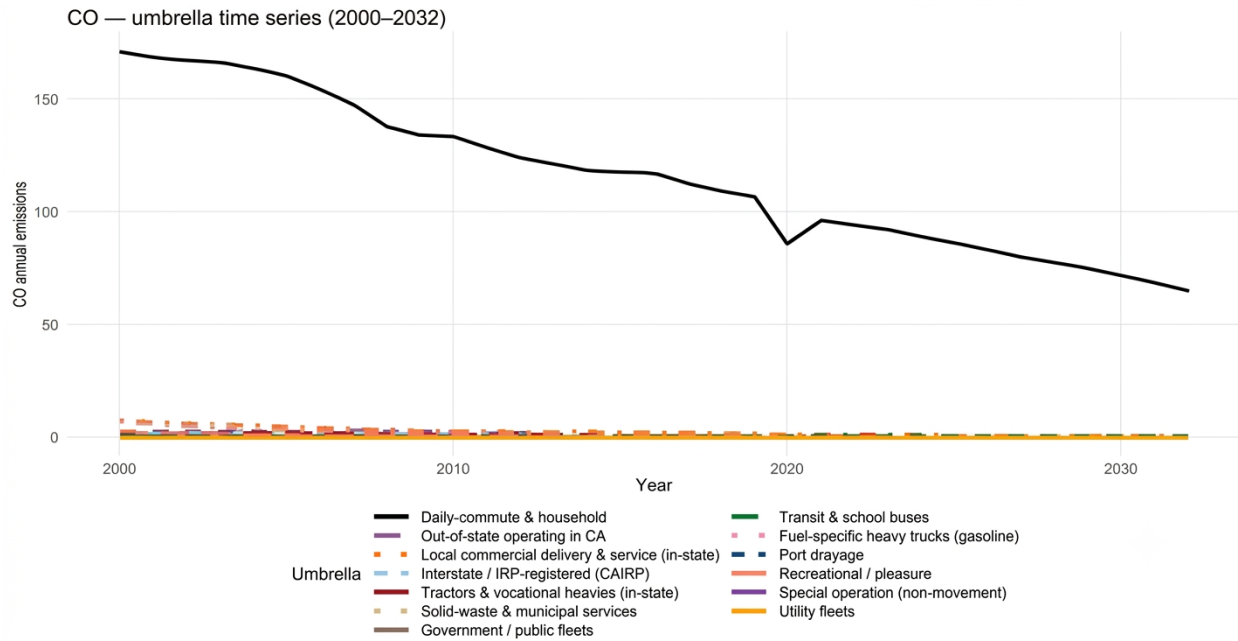
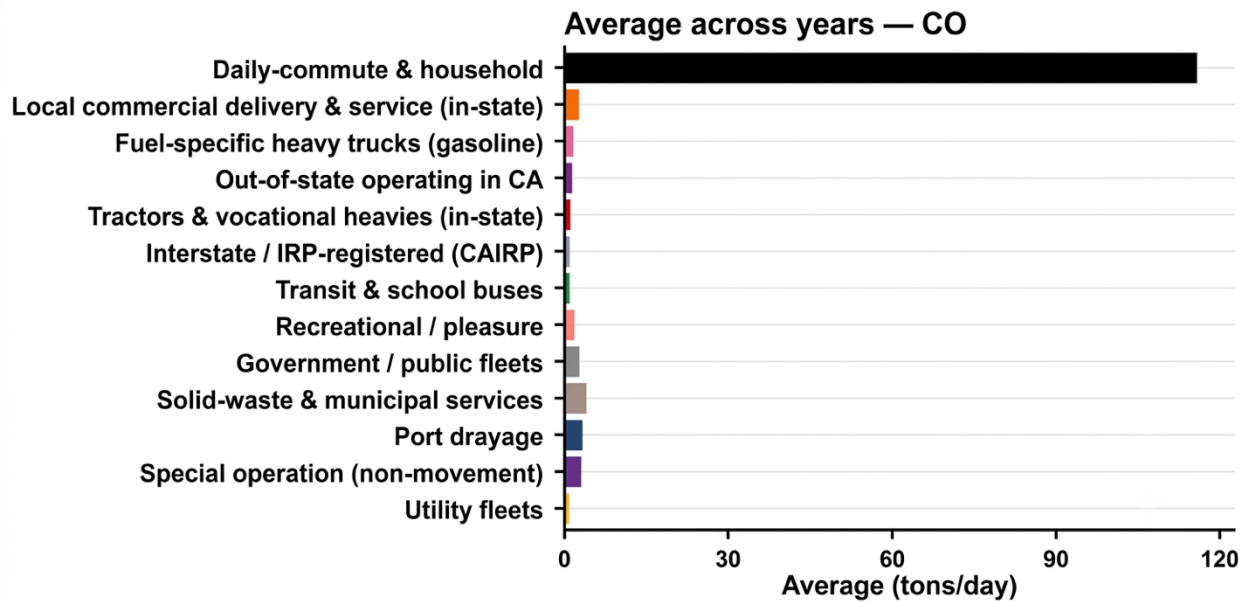


Figure 24. Contribution to CO Emissions by Vehicle Category (Averages Across 2000–2032)



CO On-Road Mobile Sources Emissions in Fresno County (2000–2032)

Annual average daily CO emissions from on-road sources in Fresno County show a consistent and substantial decline between 2000 and 2032 (Figure 22). In 2000, CO emissions exceeded 180 tons per day, but this is projected to fall below 100 tons per day by 2032. However, unlike other pollutants, passenger vehicles categorized as daily-commute & household dominate the

emissions inventory across all years, consistently represented by the large black bars. This dominance is largely due to gasoline-powered vehicles, which emit more CO per mile than diesel engines.

A key driver of the observed reduction in CO emissions during the mid-to-late 2010s is the implementation of the EPA's Tier 3 Motor Vehicle Emission and Fuel Standards program, which began phasing in on January 1, 2017. This program, aligned with California's LEV III regulations, treated vehicles and fuels as an integrated system by lowering the average gasoline sulfur content from 30 ppm to 10 ppm and tightening tailpipe emission limits (NMOG + NO_x). For carbon monoxide specifically, reducing fuel sulfur significantly improved catalytic converter performance, enabling them to operate more efficiently and reduce CO emissions more effectively. Moreover, the program extended the useful life of emissions control equipment to 150,000 miles, resulting in more sustained CO reductions per mile over a vehicle's lifetime.

This regulatory impact is clearly visible in Figure 23, where the daily-commute & household category shows a steady downward trend in CO emissions, particularly between 2017 and 2020, reflecting the effectiveness of cleaner fuels and stricter vehicle standards. Despite these improvements, the daily commute & household category remains the largest contributor, while other categories, including heavy-duty trucks, account for a much smaller share of total CO emissions. Although emissions have dropped significantly, the persistence of passenger vehicle emissions highlights the challenge of curbing CO from high volumes of gasoline-powered cars. Figure 24 further supports this, showing that the average CO emissions over the 32 years are almost entirely attributable to the daily commute & household category, with all other categories contributing minimal shares.

CO₂ On-Road Mobile Sources Emissions in Fresno County (2000–2032)

Unlike the other criteria pollutants, such as PM, SO_x, NO_x, or CO, CO₂ emissions are tightly coupled to fuel consumption and reflect broader trends in travel demand and vehicle efficiency. In Fresno County, annual average daily CO₂ emissions from on-road mobile sources remained relatively stable from 2000 through the mid-2010s, fluctuating between 13,000 and 15,000 tons per day (Figure 25). Although total emissions eventually began to decline, passenger vehicles in the daily commute & household category consistently accounted for the largest share of CO₂ emissions throughout the period, as shown by the prominent black bars.

In Figure 26, the trend lines reveal a modest downward trajectory beginning in the early 2010s, driven by overlapping fuel-efficiency and clean-fuel policies. One such policy is California's Low Carbon Fuel Standard (LCFS), which launched in 2011 and required reductions in the carbon intensity (CI) of transportation fuels. This regulation spurred a gradual transition toward renewable diesel, biodiesel, and electricity, especially among public and private fleets operating

within California. As a result, CO₂ emissions grew more slowly than vehicle miles traveled (VMT), with a noticeably gentler slope in fuel-related emissions post-2011.

Figure 25. Annual Average Daily CO₂ Emissions by Vehicle Category in Fresno County

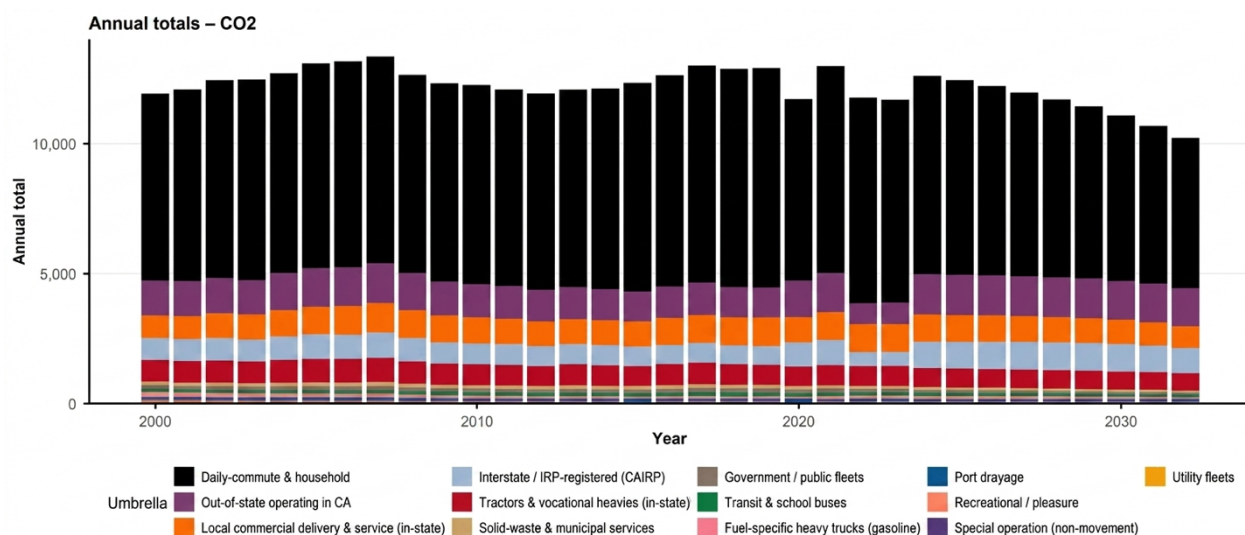


Figure 26. CO₂ Emissions Trends by Vehicle Category in Fresno County (2000–2032)

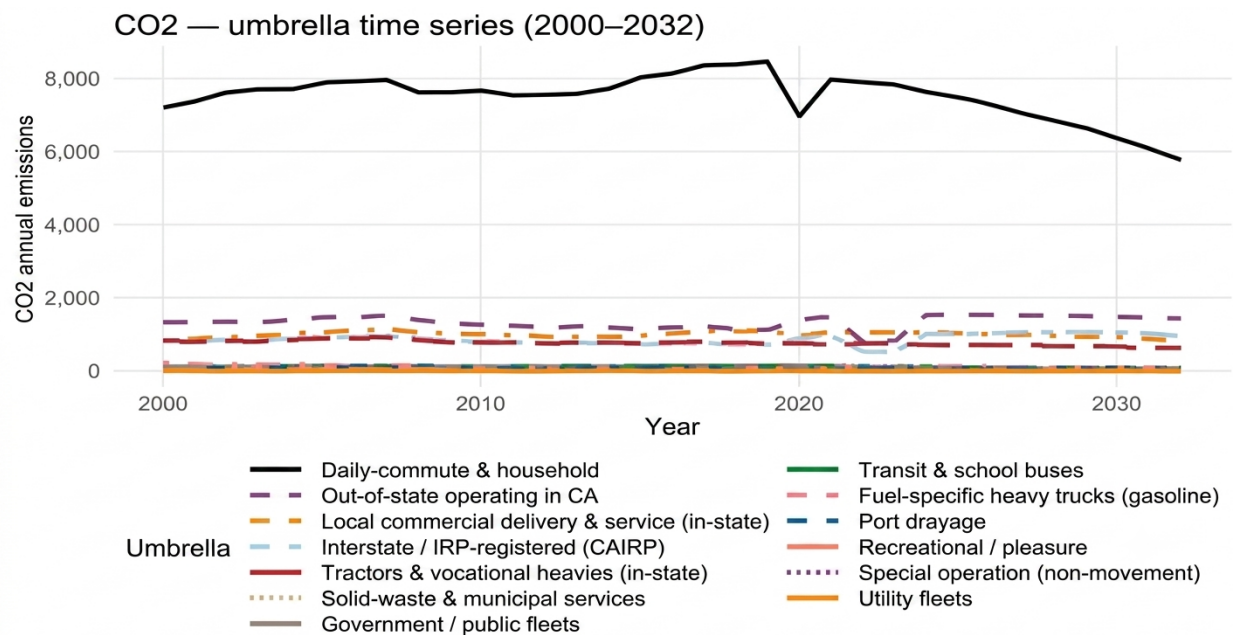
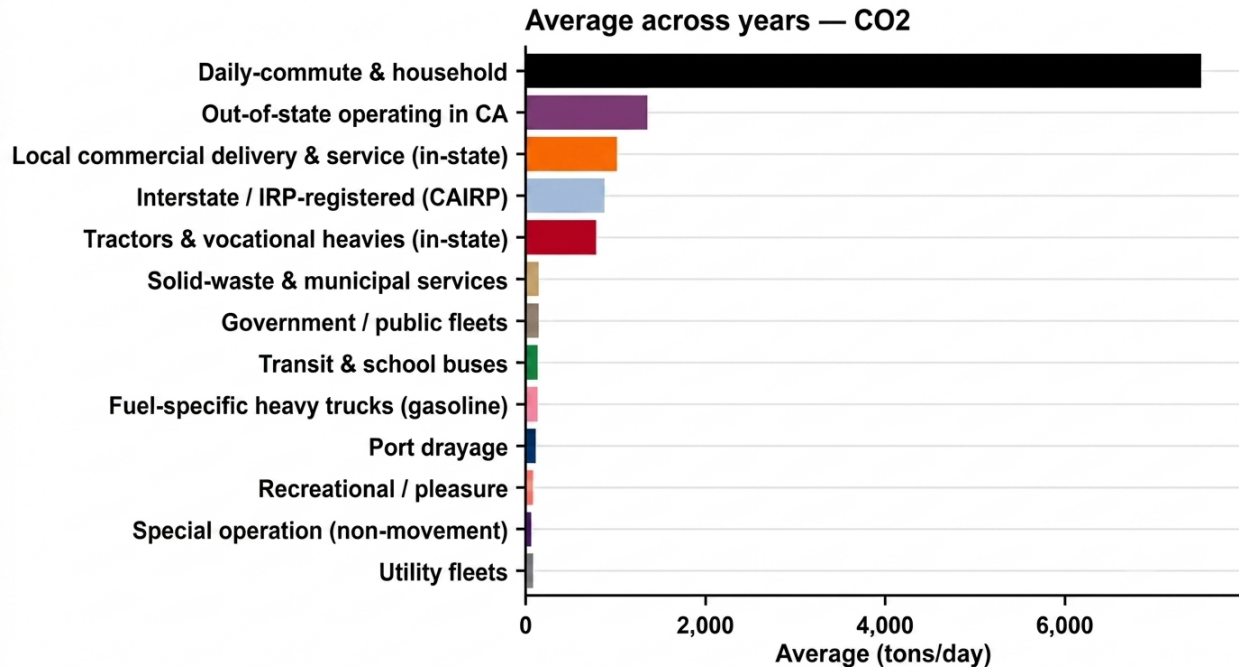


Figure 27. Contribution to CO₂ Emissions by Vehicle Category (Averages Across 2000–2032)



Additionally, medium- and heavy-duty vehicle categories, including tractors & vocational heavies, interstate IRP, and out-of-state trucks, began showing slower CO₂ emissions growth or even a flattening starting around 2015 and again post-2021. This reflects the phased-in implementation of the federal Heavy-Duty Greenhouse Gas (HD GHG) Regulations: Phase 1 (Model Years 2014–2018) and Phase 2 (Model Years 2021–2027).

These aligned federal and California standards mandate fuel-efficiency and CO₂ reduction targets for heavy-duty trucks, tractors, vocational vehicles, and, for the first time, trailers. As older trucks are retired and replaced with newer, more efficient models, CO₂ emissions per ton-mile have declined. This dynamic is visible in the freight-related umbrellas in Figure 26, which begin to flatten or grow more slowly after each regulatory phase, illustrating the regulatory impact even as total freight demand increases.

Figure 27 confirms the dominance of daily commute and household vehicles in cumulative CO₂ emissions over the 32 years. This category contributes the majority of emissions, followed distantly by out-of-state trucks, local commercial delivery, and interstate IRP-registered fleets. While heavy-duty freight plays a critical role in freight-related CO₂ emissions, its per-vehicle emissions reductions are counterbalanced by travel demand and slower fleet turnover compared to light-duty sectors.

Together, these figures demonstrate that while California’s LCFS and federal HD GHG regulations have measurably flattened emissions curves, especially in freight sectors, the overwhelming

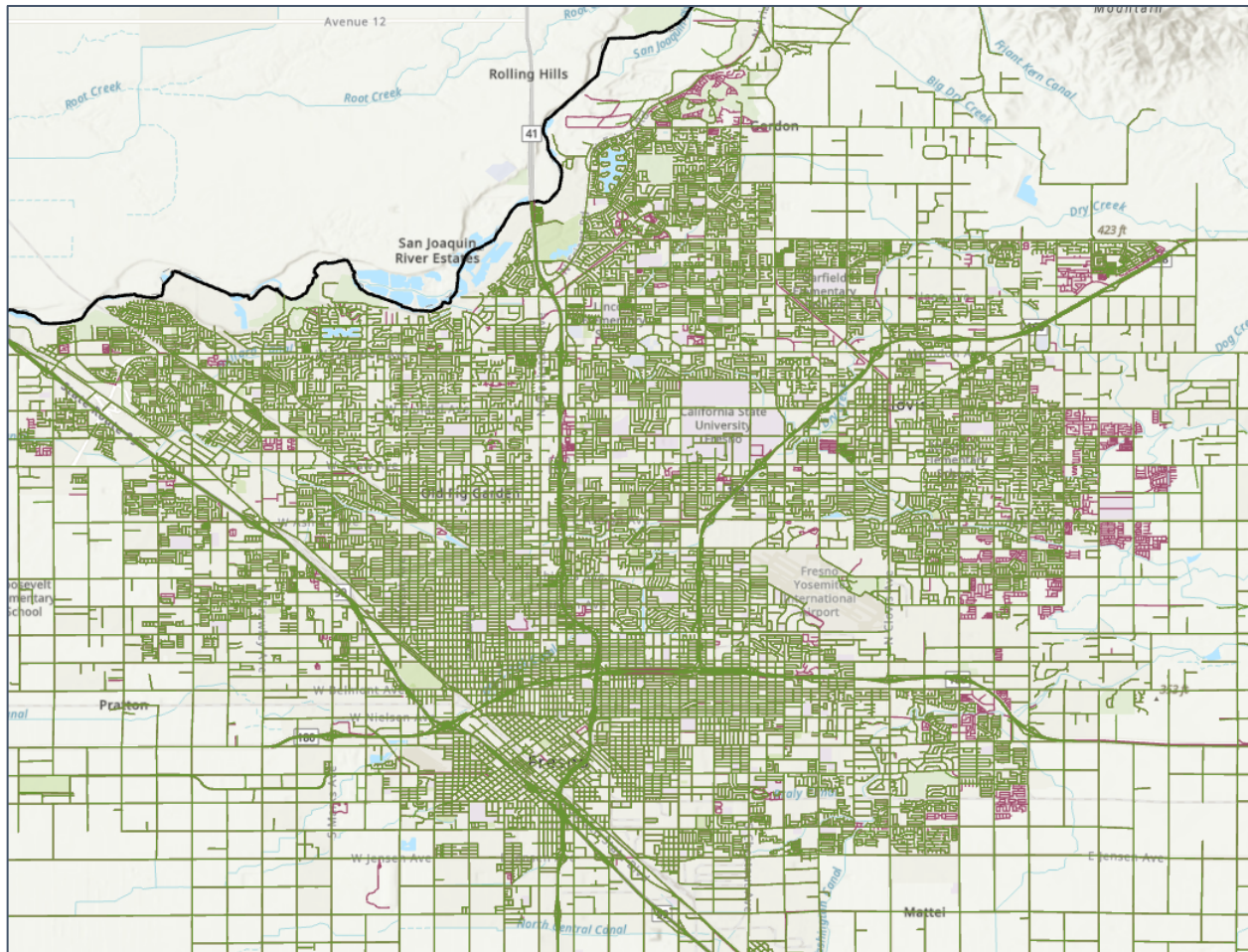
influence of passenger vehicle traffic continues to shape Fresno County's CO₂ inventory. Continued policy action and modal shifts toward low-carbon transportation options will be necessary to accelerate meaningful CO₂ reductions across all sectors of on-road transportation.

3.3 Road Network Data Analysis in Fresno County (2016–2023)

Road infrastructure in Fresno County has remained largely stable over the past five to seven years, with only minor extensions and updates across specific road classes, as evidenced by both TIGER/Line data (2018–2023) and the spatial comparison map of 2016 vs. 2023 road footprints (Figure 28). Using the TIGER/Line Road Data (2018–2023), road length data aggregated by MTFCC code classification shows the following trends:

- **Primary (S1100) and Secondary Arterials (S1200):** The backbone of the transportation network demonstrated exceptional stability. Primary roads (S1100), representing interstates and major highways, remained virtually unchanged at approximately 104 km throughout the five years. Secondary roads (S1200) showed a negligible increase of roughly 0.12 km (<0.3%). This indicates that the region's major arterial framework is mature, with no significant new highway construction occurring during this window.
- **Local Neighborhood and Rural Roads (S1400):** The most significant growth occurred in local neighborhood roads (S1400). This category increased from 3,935.4 km in 2018 to 3,985.2 km in 2023, representing a net growth of approximately 50 km (1.3%). This steady increase aligns with typical patterns of urban development, where new residential subdivisions extend the local road network at the urban periphery.
- **Ramps and Interchanges (S1630):** Ramp roads saw a notable increase from 118.6 km to 124.0 km (5.4 km). This suggests operational improvements to existing highway infrastructure, such as reconfiguring interchanges or adding access points, rather than constructing new highways.
- **Reclassification and Data Corrections:** Certain categories, such as Private Roads (S1750) and Alleys (S1740), exhibited declines. Alleys (S1740) show a decline from 23.83 km in 2018 to 22.84 km in 2023. Private roads dropped significantly from 1.13 km to 0.08 km between 2018 and 2020. These reductions likely reflect administrative reclassifications or data cleanup efforts within the TIGER database rather than the physical removal of infrastructure.
- **Other classes,** such as pedestrian walkways (S1710), service drives (S1640), stairways (S1730), and vehicular trails (S1500), showed no change or only negligible updates, indicating the maturity and stability of those infrastructure elements.

Figure 28. Roadway Network Map Refers to Changes Between 2016 (Green) and 2023 (Purple)



The visual overlay comparison of road networks in the Fresno/Clovis area between 2016 (green) and 2023 (purple) supports the quantitative TIGER data findings (Figure 28). Most of the road network remains overlapping, indicating it remained consistent with very little overall expansion. Areas of purple-only segments reveal new road additions since 2016, often at the urban fringe or in new residential/commercial developments. Some areas show minor reclassifications or realignments, visible as partial color mismatches.

In conclusion, the road network in Fresno County has undergone incremental changes, primarily within local road categories (S1400), reflecting limited development-driven growth rather than major infrastructure expansion. The stability of primary and secondary roads further confirms that the built environment has reached a relatively mature state. TIGER/Line data effectively captures these small, cumulative changes, providing insight into local development dynamics.

3.4 Land Cover in Fresno County from 1985 to 2023

Land Cover Changes in Fresno County (1985–2023)

Fresno County, located in California's San Joaquin Valley, is characterized by a diverse landscape spanning agricultural plains, urban centers, and foothills, with mountainous terrain extending eastward. The county is one of the most productive agricultural regions in the United States, with extensive farmland dominating the central and western parts of the area. In contrast, the eastern regions rise into the Sierra Nevada. As the sixth-largest county in California by land area, Fresno County covers a total area of approximately 15,570 square kilometers (6,011 square miles). Of this total, about 15,430 square kilometers (5,958 square miles) is land, while 140 square kilometers (53 square miles) is water.

Figure 29. Satellite View of Fresno County with Administrative Boundary

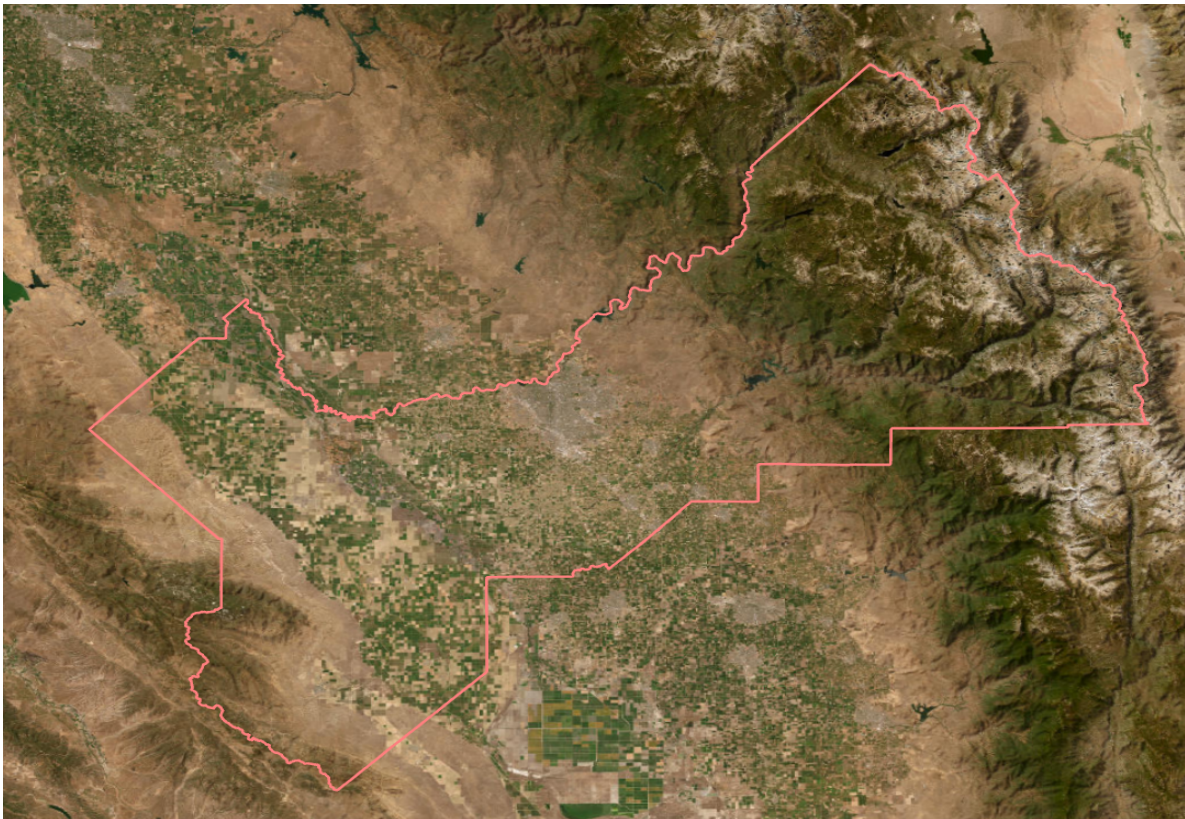


Figure 29 provides a satellite view of Fresno County with its administrative boundary outlined, highlighting the county's varied topography and dominant agricultural land cover (brown areas). Figure 30 illustrates land-cover changes over three decades, from 1990 to 2020, and reveals a distinct pattern of outward-expanding urbanization.

Figure 30. Land Use and Land Cover Changes in Fresno County (1990–2020)

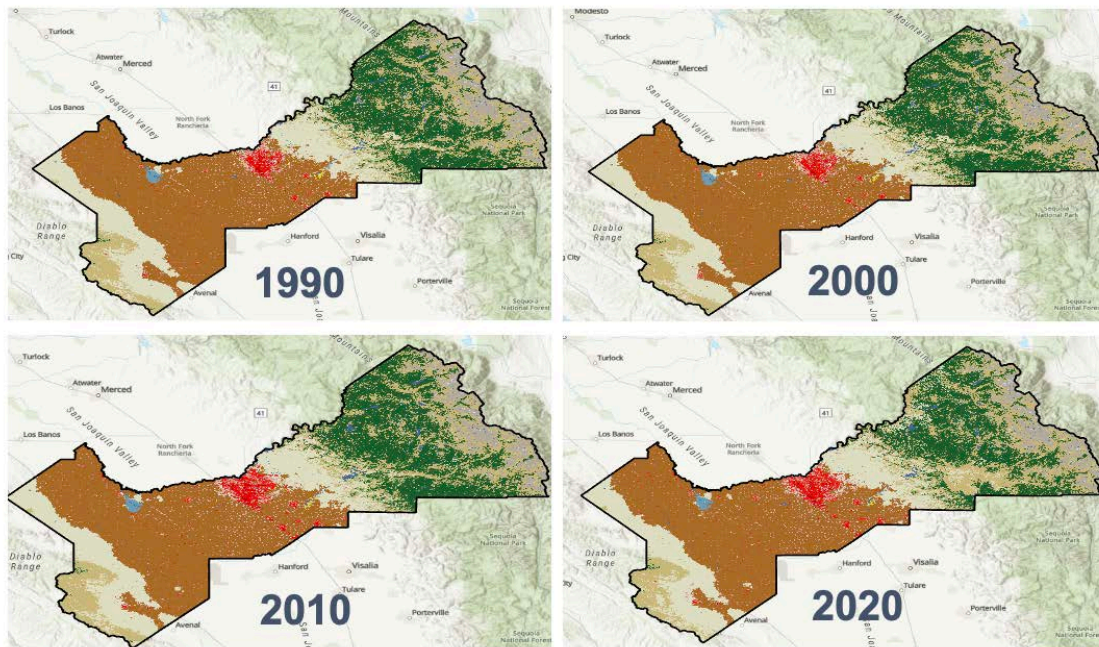
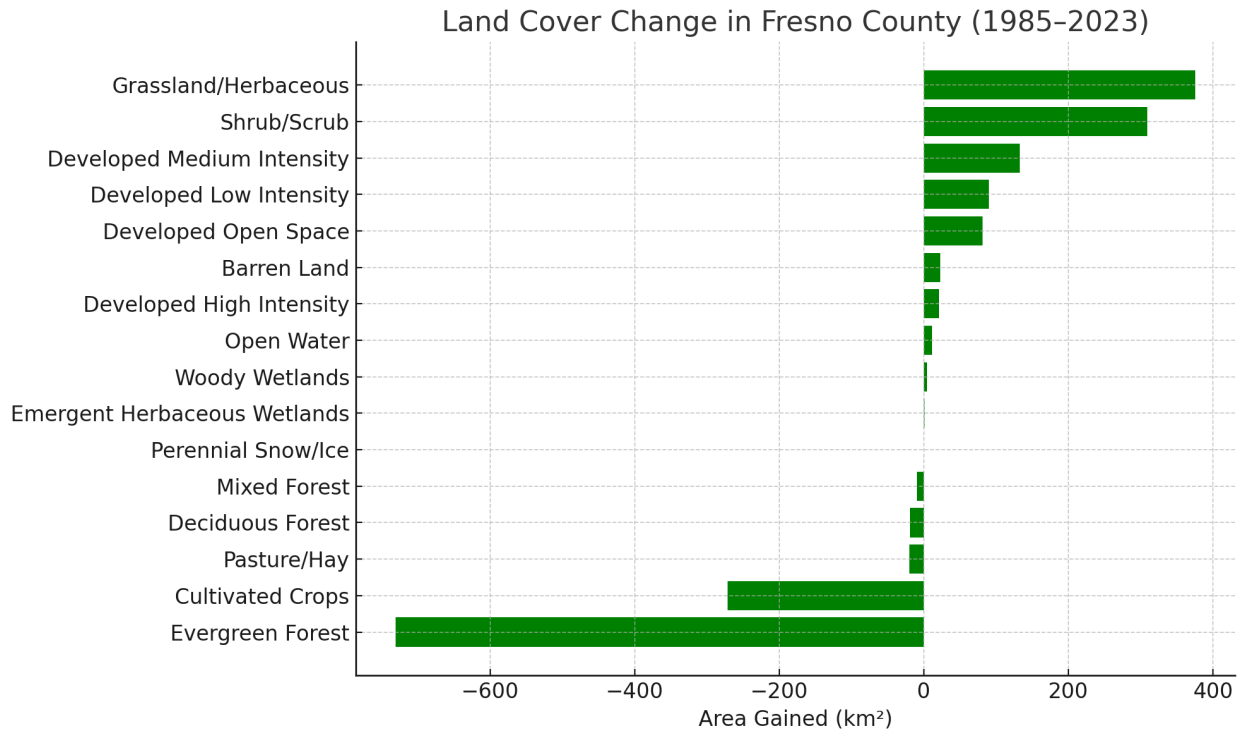


Table 3. Summary of Key Changes in Land Cover (1985–2023)

Trend Category	Land Cover Type	Change in Area (km ²)	Change (%)	Interpretation
Urban Growth	Developed Medium Intensity	133.0	87%	Significant densification of urban zones.
	Developed High Intensity	21.2	78%	Growth in commercial/industrial zones.
	Developed Low Intensity	89.7	35%	Expansion of residential subdivisions.
Vegetation Gain	Grassland/Herbaceous	375.3	14%	Likely replacing lost forest canopy.
	Shrub/Scrub	309.6	12%	Expansion of hardy, drought-tolerant flora.
Ag Decline	Cultivated Crops	-271.0	-5%	Conversion to urban use or fallowing.
	Pasture/Hay	-20.3	-63%	Sharp reduction in grazing lands.
Forest Loss	Evergreen Forest	-730.5	-24%	Major ecological loss (likely drought/fire).
	Deciduous Forest	-18.7	-32%	Significant relative decline.

Figure 31. Land Cover Changes in Fresno County By Category (1985–2023)



Based on the National Land Cover Database (NLCD) from 1985 to 2023, the land cover changes in Fresno County reveal three dominant trends: rapid urban intensification, a gradual loss of agricultural land, and a significant ecological transition from forest to shrubland (Table 3 and Figure 31).

1. Urban Expansion and Intensification: The most consistent trend in the dataset is the aggressive growth of developed land. All four Developed categories experienced substantial growth, reflecting both outward sprawl and increasing density.
 - Intensification: The fastest-growing categories by percentage were Developed Medium Intensity (+87%) and Developed High Intensity (+78%). This suggests that existing urban areas are becoming denser and more built-up.
 - Expansion: In terms of absolute land area, Developed Medium Intensity added the largest urban footprint (+133 km²), followed by Developed Low Intensity (+90 km²) and Developed Open Space (+81 km²).
 - Total Urban Growth: Collectively, the Developed categories added over 325 km² of impervious or semi-impervious surfaces to the county over the 38 years.
2. Decline in Agricultural Land: As urbanization expanded, the area of agricultural land covered shrank.

- Cultivated Crops: This is the second-largest absolute loss in the entire dataset, shrinking by 271 km² (-5%). While the percentage drop may seem small, the sheer scale of the loss of farmland is significant.
 - Pasture/Hay: This category saw the steepest relative decline of any land type, plummeting by 63%, reducing its footprint from ~32 km² in 1985 to just ~12 km² in 2023.
3. Ecological Transition (Forest Loss): A major ecological shift is visible in the data, likely reflecting the impact of long-term drought and climate stress on the Sierra Nevada portion of the county.
- Massive Forest Loss: Evergreen Forest suffered the largest absolute loss of any category, decreasing by 730.5 km² (-24%). The time-series data show a particularly sharp decline beginning around 2015–2016 (from ~2,832 km² to ~2,258 km² by 2023), which correlates with California's severe drought and tree mortality events.
 - The Replacement (Scrub & Grass): Conversely, Grassland/Herbaceous gained 375 km² (+14%) and Shrub/Scrub gained 310 km² (+12%). The data strongly suggest a landscape transition where dying evergreen forests are being replaced by scrub and grasslands.
4. Implications for Air Quality: The shift in land cover across Fresno County has direct and multifaceted impacts on regional air quality.
- Replacing vegetative cover, such as crops and orchards, with impervious surfaces (e.g., roads, rooftops) increases the urban heat island effect, which can amplify photochemical smog formation, particularly ground-level ozone, during summer months.
 - Expansion of low-density suburban development has increased vehicle miles traveled (VMT), especially in the daily commute and household category, contributing to persistent vehicular emissions of pollutants such as CO, CO₂, and PM_{2.5}.
 - Forested and natural areas in the eastern mountainous regions are generally less impacted by urban development due to topographic barriers and protected status. However, between 1985 and 2023, the region experienced substantial losses of forest cover, particularly evergreen forests, driven largely by drought and wildfires, with a pronounced decline in 2020.

While Fresno County remains dominated by agriculture, land cover data from 1985 to 2023 show a gradual yet consistent expansion of low- and medium-intensity developed land, primarily in the Fresno/Clovis metropolitan fringe. This urbanization has contributed to modest declines in cultivated crops (-5%) and notable reductions in forest cover due to drought and wildfire, rather than solely to development. The resulting land use shift has implications for regional air quality and transportation emissions.

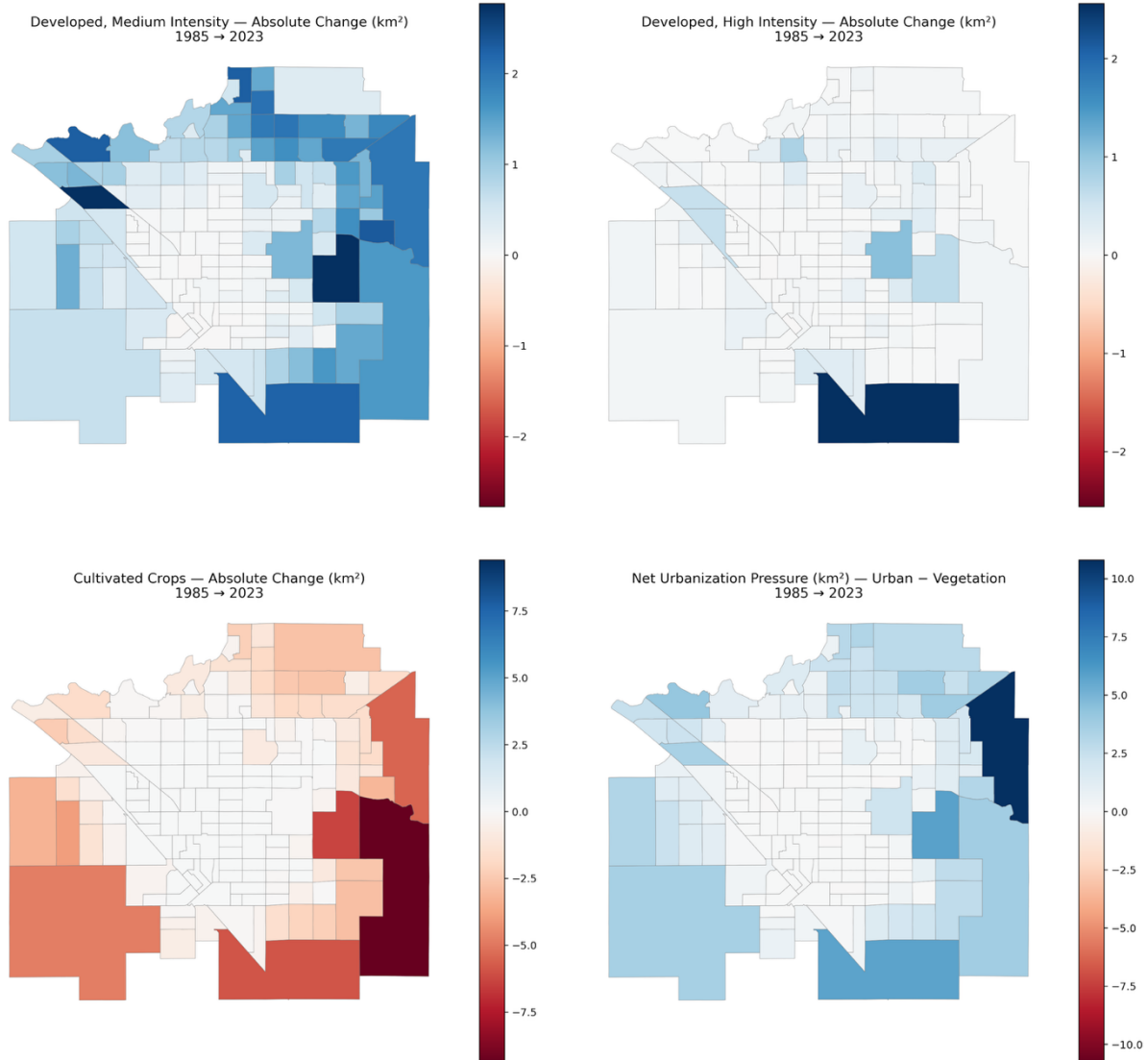
Net Urbanization Pressure from 1985 to 2023 Across the Fresno–Clovis Region

This visualization presents spatial and quantitative analyses of land-cover transformation across the Fresno–Clovis region, focusing on urban expansion, agricultural displacement, and net changes in vegetative land cover between 1985 and 2023. These patterns are critical for understanding the region’s urbanization dynamics and their environmental implications.

Expansion of Developed Land: Figure 32 displays the absolute change in Developed, Medium Intensity land (NLCD Class 23). The greatest increases are observed in the northern, southeastern, and southwestern peripheral census tracts, indicating suburban growth beyond the traditional urban core. These areas have undergone large-scale conversion to residential neighborhoods with moderate housing density and supporting infrastructure. This pattern confirms earlier findings of suburban sprawl driving the region’s development trends.

Figure 32, highlighting Developed, High Intensity change (Class 24), shows more limited expansion. Small gains appear mainly in the city center and select southern tracts, consistent with modest infill or densification rather than widespread vertical development. The dominance of medium-intensity development aligns with regional preferences for low-rise residential zoning and car-centric development.

Figure 32. Census Tract-Level Analysis of Developed Land Expansion and Vegetation Loss in Fresno/Clovis Areas (1985–2023)



Loss of Agricultural Land: Figure 32 illustrates the absolute change in Cultivated Crops (Class 82), revealing widespread losses, particularly in the eastern and southern tracts. These declines are geographically aligned with zones of urban encroachment seen in Figure 32. This supports previous conclusions that productive farmland on the urban fringe has been systematically replaced by development, rather than preserved or relocated. The conversion has occurred in some of the Central Valley's most fertile regions, raising concerns about long-term food security and land sustainability.

Net Urbanization Pressure: Urban vs. Vegetation Change: Figure 32 presents Net Urbanization Pressure, calculated as the difference between the gain in urban land cover (Classes 21–24) and the loss of vegetated land types (forest, shrubland, grassland, and wetlands). The majority of

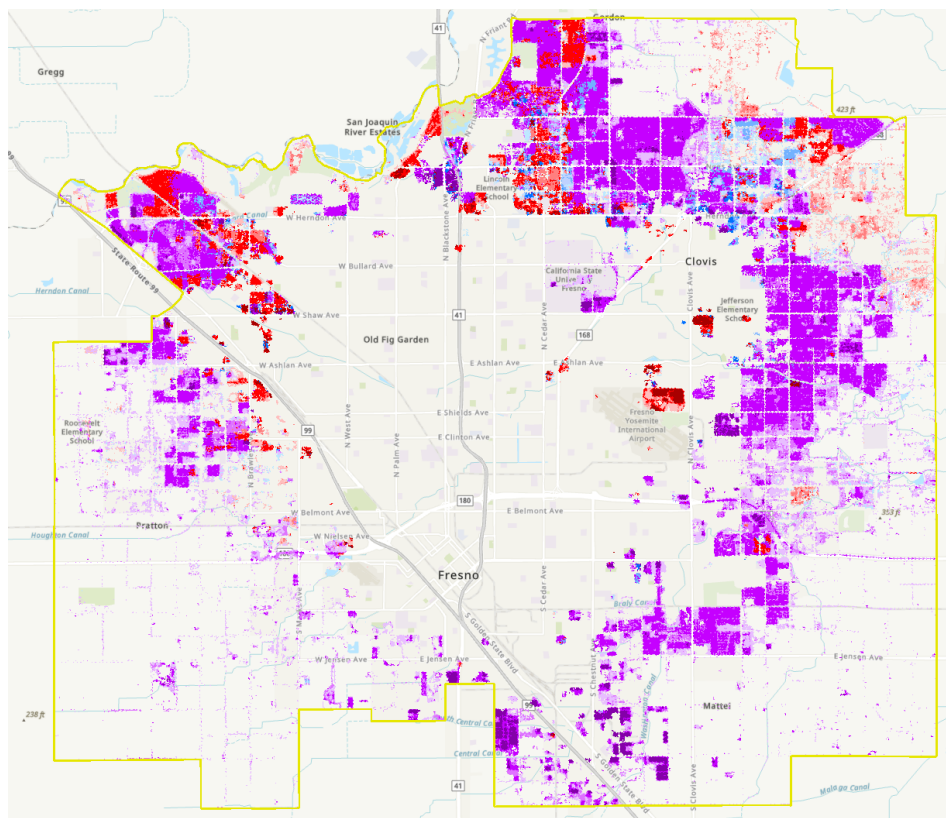
tracts, particularly in the northeast, southeast, and southwest, show positive values (in blue shades), indicating that urban expansion has far exceeded any vegetative recovery or reforestation.

- Darker blue regions indicate intensive urban pressure, where development occurred without any compensatory increase in green infrastructure.
- Tracts with values near zero, primarily in central Fresno and Clovis, indicate little net change—suggesting saturation of development or minimal vegetative alteration.
- Negative values, representing vegetation gain exceeding urban expansion, are virtually absent, reinforcing the conclusion that urbanization has been the dominant land-use trend over the past four decades.

Urban Expansion from Vegetated and Agricultural Lands in Fresno/Clovis (1985–2023)

A detailed transition analysis was conducted to identify the specific land cover types that were consumed to fuel the region's urban expansion. By tracking pixel-level transitions from vegetative and agricultural classes (NLCD codes 71, 81, 82) to developed urban classes (NLCD codes 21, 22, 23, 24), the specific origins of the new urban footprint were quantified (Figure 33).

Figure 33. Detailed Map of Vegetation Changes by Parcel (1985–2023)



Total Urban Expansion: Between 1985 and 2023, the Fresno-Clovis area experienced a total urban expansion of approximately 134.33 km² derived from previously vegetated or agricultural lands (Table 4).

Table 4. Land Use Transitions to Urban Classes: Herbaceous, Pasture, and Cropland Conversions (1985–2023)

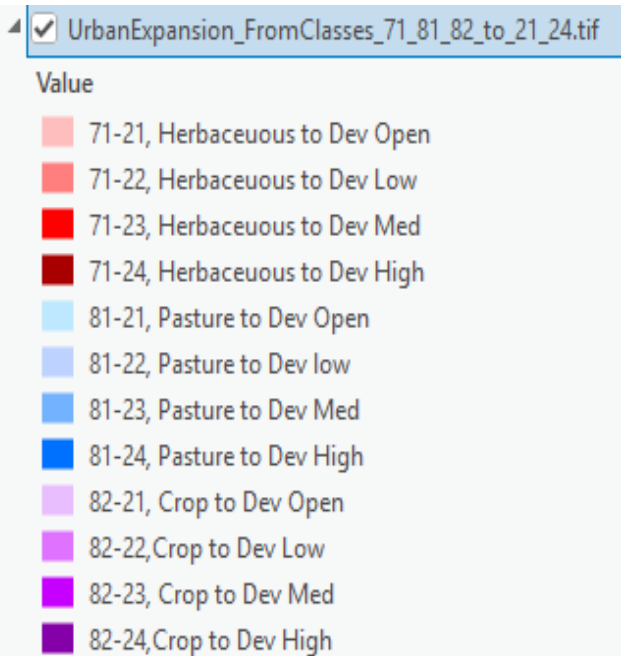
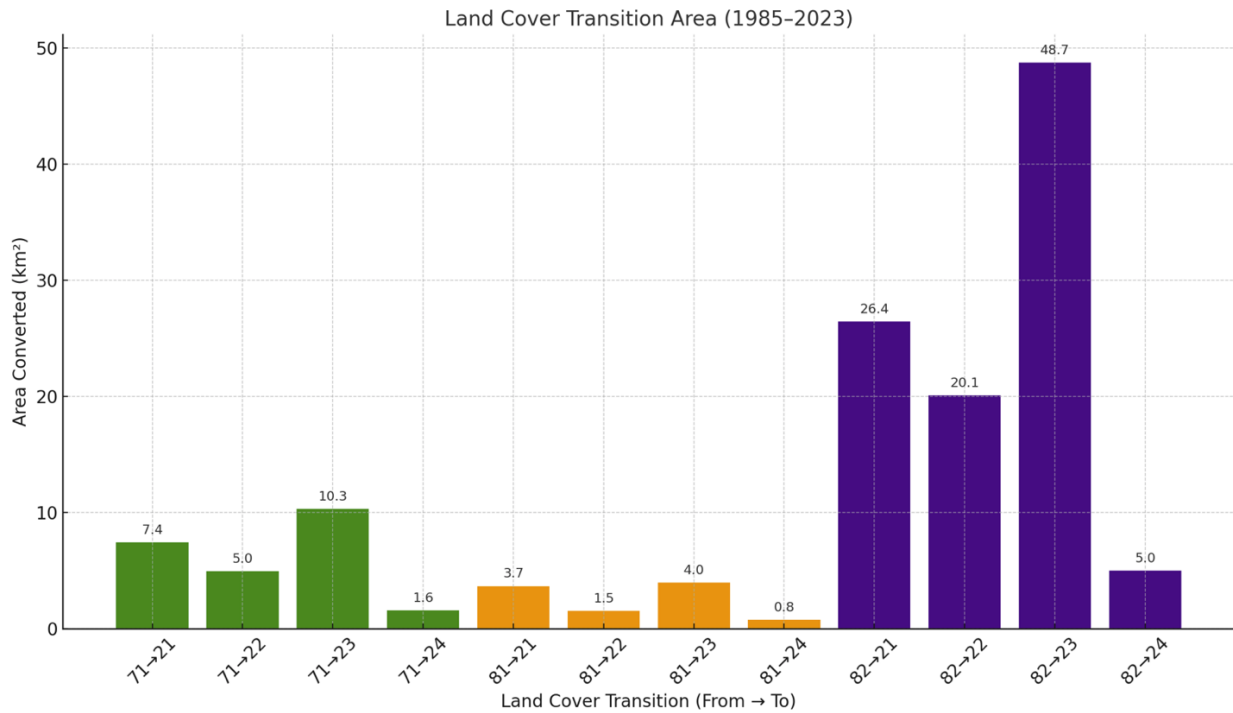
Value	From → To	Count	Area (km ²)	 UrbanExpansion_FromClasses_71_81_82_to_21_24.tif Value 71-21, Herbaceous to Dev Open 71-22, Herbaceous to Dev Low 71-23, Herbaceous to Dev Med 71-24, Herbaceous to Dev High 81-21, Pasture to Dev Open 81-22, Pasture to Dev low 81-23, Pasture to Dev Med 81-24, Pasture to Dev High 82-21, Crop to Dev Open 82-22, Crop to Dev Low 82-23, Crop to Dev Med 82-24, Crop to Dev High
1	71 → 21	8,225	7.40 km ²	
2	71 → 22	5,499	4.95 km ²	
3	71 → 23	11,445	10.30 km ²	
4	71 → 24	1,753	1.58 km ²	
5	81 → 21	4,072	3.66 km ²	
6	81 → 22	1,693	1.52 km ²	
7	81 → 23	4,393	3.95 km ²	
8	81 → 24	837	0.75 km ²	
9	82 → 21	29,351	26.42 km ²	
10	82 → 22	22,295	20.07 km ²	
11	82 → 23	54,152	48.74 km ²	
12	82 → 24	5,535	4.98 km ²	

Figure 34. Land Cover Transition Area (1985–2023)



Dominance of Agricultural Conversion: The analysis reveals that active farmland was the overwhelming primary source of new development (Figure 34).

Cultivated Crops (82) to Urban: This transition accounted for 100.20 km² of new urban area. Approximately 75% of all land converted to urban use during these 38 years was previously active cropland. This confirms that the region's “sprawl” has occurred almost exclusively at the expense of productive agricultural output.

3.5 Time-Series Regression Results

Table 5. GLS-AR(1) Regression Results

Variable	PM2.5 (p)	PM10 (p)	NO ₂ (p)	CO (p)	O ₃ (p)
Household VMT	-1.55 (0.10)	-5.03 (0.01)*	0.41 (0.07)	0.08 (0.32)	0.05 (0.40)
Freight VMT	0.72 (0.26)	1.34 (0.26)	0.14 (0.34)	0.03 (0.45)	-0.02 (0.52)
Urbanization	-2.54 (0.01)*	1.67 (0.57)	-2.67 (0.00)***	-0.12 (0.28)	0.07 (0.36)

Coefficients are standardized; * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Table 5 shows the GLS regression results, which indicate that the relationship between transportation activity, urbanization, and air quality is largely driven by long-term trends rather than direct causal effects. For PM_{2.5}, urbanization exhibits a statistically significant negative association ($\beta = -2.54$, $p = 0.01$), while household VMT ($\beta = -1.55$, $p = 0.10$) and freight VMT ($\beta = 0.72$, $p = 0.26$) are not statistically significant. This suggests that increases in developed land coincide with reductions in PM_{2.5} concentrations, likely reflecting broader regulatory improvements and technological advancements that occurred alongside urban expansion.

For PM₁₀, household vehicle miles traveled is negative and statistically significant ($\beta = -5.03$, $p = 0.01$), whereas freight VMT ($\beta = 1.34$, $p = 0.26$) and urbanization ($\beta = 1.67$, $p = 0.57$) are not significant. This indicates that PM₁₀ concentrations have declined despite increases in household travel. However, given the time-series nature of the data, this negative relationship likely reflects shared long-term trends rather than a direct causal effect of increased travel reducing pollution.

The NO₂ results show a strong and highly significant negative association with urbanization ($\beta = -2.67$, $p < 0.01$). In contrast, household VMT ($\beta = 0.41$, $p = 0.07$) is only marginally significant, and freight VMT ($\beta = 0.14$, $p = 0.34$) is not significant. This pattern is consistent with the widespread adoption of cleaner vehicle technologies and stricter emissions regulations, which have reduced NO₂ concentrations over time despite increasing urban development and travel demand.

For CO and O₃, none of the explanatory variables are statistically significant. The lack of significance for CO suggests that its long-term decline is primarily driven by technological improvements such as catalytic converters and fuel standards, rather than variation in transportation activity captured in the model. Similarly, the absence of significant relationships for O₃ is consistent with its role as a secondary pollutant, whose formation depends on nonlinear atmospheric chemistry involving nitrogen oxides, volatile organic compounds, and meteorological conditions, rather than direct emissions alone.

Table 6. First-Difference Regression Results

Variable	$\Delta PM_{2.5}$ (p)	ΔPM_{10} (p)	ΔNO_2 (p)	ΔCO (p)	ΔO_3 (p)
Δ Household VMT	-1.61 (0.06)	-3.87 (0.00)***	0.12 (0.41)	0.04 (0.38)	0.02 (0.44)
Δ Freight VMT	0.35 (0.28)	0.28 (0.31)	0.06 (0.52)	0.01 (0.60)	-0.01 (0.65)
Δ Urbanization	-0.22 (0.47)	0.15 (0.55)	-0.31 (0.22)	-0.05 (0.33)	0.03 (0.49)

Δ denotes year-to-year change; * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Table 6 shows the results from first-difference regression. The first-difference models provide a more stringent test by removing long-term trends and focusing on year-to-year changes. For PM_{2.5}, changes in household VMT are marginally significant and negative ($\beta = -1.61$, $p = 0.06$), while changes in freight VMT and urbanization are not statistically significant. This suggests limited evidence that short-term fluctuations in household travel may influence PM_{2.5} concentrations, though the relationship is not robust.

For PM₁₀, changes in household VMT remain negative and highly significant ($\beta = -3.87$, $p < 0.01$), even after removing long-term trends. This indicates a consistent and robust association between household travel activity and PM₁₀ concentrations, making PM₁₀ the only pollutant in this study for which the relationship persists across both modeling approaches.

In contrast, no statistically significant relationships are observed for NO₂, CO, or O₃ in the first-difference models. This implies that short-term changes in transportation activity and urbanization do not meaningfully explain year-to-year variation in these pollutants. Instead, their dynamics appear to be driven primarily by longer-term structural factors, regulatory changes, and, in the case of O₃, complex atmospheric processes.

4. Summary & Conclusions

This study integrated long-term air quality monitoring data, on-road mobile-source emission inventories (EMFAC), road network analysis (TIGER), and land-cover change assessments (NLCD) to evaluate the spatiotemporal evolution of transportation-related air pollution impacts in Fresno County from 1985 to 2032. Three distinct but interconnected key trends were found through the analysis:

1. Air quality improvements and regulatory success: Between 1991 and 2023, Fresno County achieved significant reductions in ambient concentrations of major criteria pollutants, particularly those associated with mobile sources.
 - a. Tailpipe emissions: Primary combustion pollutants such as nitrogen dioxide (NO_2) and carbon monoxide (CO) declined by over 50–60%. In contrast, sulfur dioxide (SO_2) was effectively eliminated as a local concern due to Ultra-Low Sulfur Diesel (ULSD) regulations.
 - b. Particulate matter ($\text{PM}_{2.5}$ and PM_{10}): Fine particulate matter ($\text{PM}_{2.5}$) concentrations dropped from around $30 \mu\text{g}/\text{m}^3$ in the early 1990s to below $12 \mu\text{g}/\text{m}^3$ in recent years, largely driven by cleaner diesel engine standards. However, PM_{10} reductions have been less consistent due to the persistence of non-exhaust emissions, resuspended dust such as brake and tire wear, and wildfire events.
 - c. Source composition crossover: A fundamental shift occurred around 2018, where passenger vehicles surpassed heavy-duty diesel trucks as the primary source of on-road $\text{PM}_{2.5}$ emissions. While heavy-duty exhaust has significantly declined, non-exhaust emissions (brake and tire wear) from passenger vehicles now dominate the inventory, decoupling pollution from engine technology and linking it directly to vehicle volume.
2. Road network stability vs. usage intensity: The topological analysis of the road network (2018–2023) indicates a mature infrastructure with minimal expansion in primary or secondary arteries.
 - a. Network stasis: Total lengths of major highways (S1100) and secondary roads (S1200) remained virtually unchanged, indicating that no significant new regional capacity was added.
 - b. VMT growth: Despite the static network, Vehicle Miles Traveled (VMT) for households engaged in daily commuting has continued to rise, recovering to near pre-pandemic levels of 19 million miles per day. This divergence between static

infrastructure and growing usage intensity exacerbates congestion-related non-exhaust emissions.

3. Land cover transformation and urban sprawl: The landscape of Fresno County has undergone a significant transition characterized by low-density urban expansion at the expense of agricultural and natural lands.
 - a. Urbanization: Impervious developed land (Classes 21–24) expanded significantly, with new development occurring primarily on the urban periphery rather than through infill.
 - b. Agricultural and ecological loss: This urban growth was fueled by the conversion of productive cultivated land and pastureland. Simultaneously, the region experienced a loss of forest cover in the foothills, particularly evergreen forests, likely due to drought, disease, and wildfire, further reducing the landscape's natural capacity to retain pollutants.

In addition, the time-series regression results indicate that many of the associations observed in the GLS models are influenced by shared long-term trends, particularly the simultaneous increase in urbanization and decline in pollutant concentrations over time. The first-difference results confirm that most of these relationships do not persist after removing trends, with the notable exception of PM₁₀, where household vehicle activity shows a consistent and statistically significant association. These findings highlight the importance of distinguishing between trend-driven correlations and robust relationships when interpreting time-series regression results in environmental and transportation studies.

The synthesis of these findings highlights a critical divergence in Fresno County's environmental trajectory: While fuel and engine technological mandates have successfully mitigated the diesel problem, land-use patterns are exacerbating the VMT volume problem.

The successful elimination of heavy-duty truck exhaust stands as a major victory for air quality policy, proving that regulations like the Truck and Bus Rule work. However, the persistence of PM₁₀ and the new dominance of passenger-vehicle emissions suggest that the region has reached the limits of what engine standards alone can achieve. The land cover and road data reveal the structural driver: The region is actively expanding its urban footprint outward, converting agricultural land into low-density residential zones that necessitate private vehicle dependence.

Consequently, the challenge for the next decade has shifted from the tailpipe to the built environment. With non-exhaust PM₁₀ now a leading pollutant and VMT increasing due to daily commuting and household use, which together account for a major share of remaining emissions, future air quality improvements will depend more on managing urban growth, reducing sprawl,

and decoupling development from vehicle dependence. The integration of emission trends, land conversion, and road network stability clearly showed that, while air quality is improving, sprawl-induced growth and persistent VMT present ongoing challenges. These findings emphasize the importance of coordinated land-use, transportation, and emissions policies in shaping sustainable urban futures.

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