CASE STUDY

JUNE 2023

Particulate matter emissions from U.S. gasoline light-duty vehicles and trucks

TRUE Initiative U.S. remote sensing database case study

Michelle Meyer, Tanzila Khan, Tim Dallmann, Zifei Yang

INTRODUCTION

Vehicle emissions are a major environmental health hazard, contributing to air pollution which causes increased rates of respiratory and cardiovascular diseases and premature deaths. In the United States, passenger vehicles are one of the largest sources of human-caused fine particulate matter ($PM_{2.5}$), which is associated with approximately 100,000 premature deaths per year.[1] Addressing emissions from gasoline light-duty vehicles (LDVs) is also an environmental justice issue. Elevated levels of air pollution near high-traffic areas contribute to inequities in health impacts, and people of color are exposed to an estimated 46% more $PM_{2.5}$ from gasoline LDVs compared to White people in the United States.[2]

The U.S. Environmental Protection Agency (EPA) has regulated tailpipe emissions since the 1970s, initially setting emission limits for hydrocarbons (HC), carbon monoxide (CO), and nitrogen oxides (NO_x).[3] Emission limits for PM were later introduced but initially only applied to diesel vehicles.[4] The agency has since progressively tightened PM emission limits and extended the application to all fuel and vehicle types, including light-duty gasoline vehicles.[5] Under the fully phased-in Tier 3 standards, all LDVs are subject to PM emissions limits of 3 mg/mile and 6 mg/mile, respectively, for the Federal Test Procedure (FTP) and US06 test cycles.[6]

In April 2023, EPA announced plans to further lower PM limits for LDVs with the proposed multipollutant emission standards for light- and medium-duty vehicles of model year 2027 and later.[7] The proposal indicates a lower PM limit of 0.5 mg/mile and the addition of the cold (20 °F) temperature FTP test for regulating PM emissions. The addition of the cold temperature test helps to account for higher PM emissions from gasoline vehicles during cold starts at low ambient temperatures, when engine and catalysts need longer

1 Sumil K. Thakrar, Srinidhi Balasubramanian, Peter J. Adams, Inês M. L. Azevedo, Nicholas Z. Muller, Spyros N. Pandis, Stephen Polasky, C. Arden Pope III, Allen L. Robinson, Joshua S. Apte… Jason D. Hill*, "Reducing Mortality from Air Pollution in the United States by Targeting Specific Emission Sources," *Environmental Science & Technology Letters* 7, no. 9 (September 8, 2020): 639–45, https://doi.org/10.1021/acs.estlett.0c00424.

2 Christopher W. Tessum, David A. Paolella, Sarah E. Chambliss, Joshua S. Apte, Jason D. Hill, and Julian D. Marshall, "$PM_{2.5}$ Polluters Disproportionately and Systemically Affect People of Color in the United States," *Science Advances* 7, no. 18 (April 2021): eabf4491, https://doi.org/10.1126/sciadv.abf4491.

3 U.S. Environmental Protection Agency, "Timeline of Major Accomplishments in Transportation, Air Pollution, and Climate Change," (June 27, 2016), https://www.epa.gov/transportation-air-pollution-and-climate-change/timeline-major-accomplishments-transportation-air.

4 U.S. EPA, "Light-Duty Trucks: Tier 0, Tier 1, and Clean Fuel Vehicle (CFV) Exhaust Emission Standards," (March 2016), https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P100O9ZL.pdf.

5 "United States: Cars and Light-Duty Trucks", DieselNet, accessed May 16, 2023, https://dieselnet.com/standards/us/ld.php#epa

6 U.S. Environmental Protection Agency, "EPA Sets Tier 3 Tailpipe and Evaporative Emission and Vehicle Fuel Standards," (March 2014), https://nepis.epa.gov/Exe/ZyPDF.cgi/P100HVZQ.PDF?Dockey=P100HVZQ.PDF.

7 Office of the Federal Register, "40 CFR Parts 85, 86, 600, 1036, 1037, and 1066 Multi-Pollutant Emissions Standards for Model Years 2027 and Later LightDuty and Medium-Duty Vehicles," (May 2023), https://www.govinfo.gov/content/pkg/FR-2023-05-05/pdf/2023-07974.pdf. https://www.epa.gov/system/files/documents/2023-04/lmdv-multi-pollutant-emissions-my-2027-nprm-2023-04.pdf

to warm up.[8] EPA also proposes an accelerated phase-in of standards for PM emissions relative to other criteria pollutants, suggesting implementation for 100% of the new fleet by 2028.

In addition to increasingly stringent emission limits, another trend impacting gasoline LDV emissions is a shift in fuel injection technologies. Gasoline direct injection (GDI) technology was first introduced to the U.S. LDV market in 2008 and gained momentum relatively quickly, growing from a market share of just under 10% in 2010 to nearly 50% in 2015 (Figure 1).[9] As of 2021, GDI vehicles represent an approximate 53% share of new U.S. LDV sales. This shift was largely due to the higher fuel efficiency and power of GDI vehicles compared to conventional port fuel injection (PFI) vehicles.[10] Additionally, GDI engines are often coupled with turbochargers that help to increase vehicle power while allowing for downsizing of the engine for better fuel economy.[11] Vehicles with GDI engines were found to be, on average, 8% more fuel efficient than those with PFI engines.[12]

Though GDI vehicles have better fuel economy than PFI vehicles, early GDI engines showed comparatively high PM emissions. One analysis showed that 2008–2014 model year GDI vehicles had PM emissions at least twice as high as PFI vehicles that were certified to the same standards.[13] The same study also found that the GDI vehicles certified to relatively more stringent PM standards had lower PM emissions than older GDI vehicles, indicating that PM emissions have likely declined to meet Tier 3 PM emissions limits. However, there is limited literature on the comparison between Tier 3 certified GDI and PFI vehicle PM emissions.

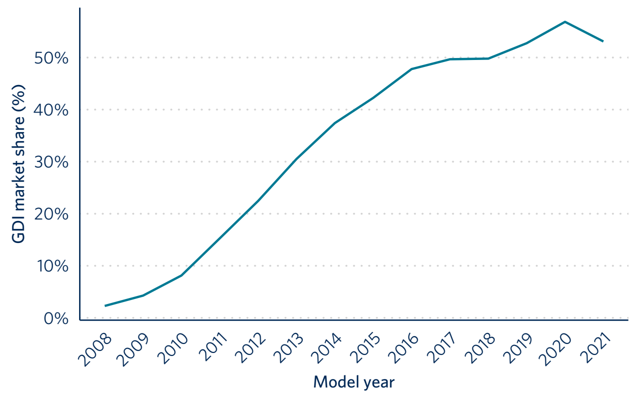


Figure 1. Trend of average GDI shares in the U.S. light-duty vehicle market across all manufacturers and vehicle types.

This analysis explores the impact of the shift towards GDI engines on real-world PM emissions from the U.S. light-duty fleet and the associated regulatory implications. We use a database of tens of millions of measurements of in-use vehicle emissions previously compiled by The Real Urban Emissions (TRUE) Initiative.[14] This report builds on a previous examination of carbon monoxide (CO), nitrogen monoxide (NO), and hydrocarbon (HC) emissions trends from LDVs by model year, adding an analysis of ultraviolet (UV) smoke measurements as an estimate of PM emissions.[15] Data collected in 2019–2021 have been added to the database since the last analysis, allowing for an evaluation of more recent model year vehicles. In addition to real-world data, we also use U.S. EPA's laboratory-based official certification test data to evaluate the PM emissions performance of GDI vehicles compared to PFI vehicles.

8 S. M. Platt, I. El Haddad, S. M. Pieber, A. A. Zardini, R. Suarez-Bertoa, M. Clairotte, K. R. Daellenbach, R.-J. Huang, J. G. Slowik... and A. S. H. Prévôt "Gasoline Cars Produce More Carbonaceous Particulate Matter than Modern Filter-Equipped Diesel Cars," Scientific Reports 7, no. 1 (July 13, 2017): 4926, https://doi.org/10.1038/s41598-017-03714-9. PM emissions are higher during cold starts particularly at low temperatures due to poor combustion efficiency resulting from low engine cylinder temperature and increased friction due to high viscosity of fuel, and low catalyst temperatures and efficiencies.

9 U.S. Environmental Protection Agency, "The 2022 EPA Automotive Trends Report," (December 2022), https://www.epa.gov/system/files/documents/2022-12/420r22029.pdf.

10 U.S. Environmental Protection Agency, "The 2022 EPA Automotive Trends Report."

11 "The 2022 EPA Automotive Trends Report."

12 Sanjam Singh, "Comparison of Fuel Economy and Gaseous Emissions of Gas-Direct Injection versus Port-Fuel Injection Light Duty Vehicles Based on Real-World Measurements," (2018), https://repository.lib.ncsu.edu/bitstream/handle/1840.20/35195/etd.pdf?sequence=1.

13 Georges Saliba, Rawad Saleh, Yunliang Zhao, Albert A. Presto, Andrew T. Lambe, Bruce Frodin, Satya Sardar, Hector Maldonado, Christine Maddox, Andrew A. May... Allen L. Robinson, "Comparison of Gasoline Direct-Injection (GDI) and Port Fuel Injection (PFI) Vehicle Emissions: Emission Certification Standards, Cold-Start, Secondary Organic Aerosol Formation Potential, and Potential Climate Impacts," *Environmental Science & Technology* 51, no. 11 (June 6, 2017): 6542–52, https://doi.org/10.1021/acs.est.6b06509.

14 Yoann Bernard, Tim Dallmann, Uwe Tietge, Huzeifa Badshah, and John German, *Development and application of a United States real-world vehicle emissions database*, (Washington, DC: ICCT, 2020), https://theicct.org/publications/true-us-database-development-oct2020.

15 Yoann Bernard, Tim Dallmann, Uwe Tietge, Huzeifa Badshah, and John German, *Emissions deterioration of U.S. gasoline light-duty vehicles and trucks: TRUE Initiative U.S. remote sensing database case study,* (Washington, DC: ICCT, 2020), https://www.trueinitiative.org/media/791471/us-emissions-deterioration.pdf.

DATA OVERVIEW

This analysis uses real-world emissions data from the TRUE U.S. database,[16] which was compiled by the ICCT and outlined in a 2020 TRUE report.[17] The original database included remote sensing measurements collected in 2010–2018 by the Colorado Department of Public Health & Environment and in 2015–2018 by the Virginia Department of Environmental Quality. Since the publication of the original report, Colorado data collected in 2019 and Virginia data collected in 2019–2021 were added to the database. The database is currently comprised of nearly 70 million remote sensing measurements which cover a wide range of ambient and driving conditions, thus providing a good representation of emissions during real-world operation.

Particulate matter mass emissions are not measured directly by remote sensing systems. For this analysis, we use the measurement of UV smoke as a proxy for PM emissions to assess long-term trends, as has been done in previous studies.[18] The measurement of ultraviolet (UV) smoke is expressed as the ratio of exhaust plume opacity measured at a wavelength of 230 nm to the amount of fuel burned at the time of measurement. The interaction of the remote sensing light beam with exhaust particles depends several factors, which can vary considerably across vehicles in a fleet and even for individual vehicles across operating modes. While the opacity measurement gives some information about particulate matter emissions, it is fundamentally different than methods used to for measuring particulate matter in regulatory certification and compliance testing. Given these considerations, UV smoke data from remote sensing is best suited for comparative analyses. For example, the UV smoke measurement would not be suitable for determining if an individual vehicle is emitting above the official certification limit but could identify if a group of vehicles are high emitters compared to the rest of the fleet and be used to assess relative trends over time.

This analysis uses a subset of data most relevant to the study of PM emissions from gasoline LDVs and light-duty trucks (LDTs) with GDI and non-GDI engines.[19] Data from heavy-duty vehicles and light-duty diesel vehicles are not included in the analysis. Vehicles of model year 2005 and later are analyzed, as the uptake of GDI engines began shortly after 2005. Additionally, measurements are filtered out based on several criteria. Vehicle specific power (VSP) is a surrogate for engine load calculated using speed, acceleration, and road slope. This analysis uses measurements with a vehicle specific power (VSP) of > 0 to exclude data under low engine loads.[20] Additionally, UV smoke measurements under -20 g PM/kg fuel or above 200 g PM/kg fuel are considered implausible and are filtered out.[21]

Finally, although the Colorado dataset includes measurements from as early as 2010, only data collected from 2015 and later are used. This is due to a remote sensing instrumentation change in 2015 from Opus model RSD4600 to the Opus model RSD5000, which led to a difference in the average UV smoke measurements. To eliminate the influence of the instrumentation change, only data captured in 2015 and later using the Opus RSD5000, the same instrument used in Virginia, are used in this analysis.

The resulting subset of data contains 7.4 million measurements of LDVs and 11.4 million measurements of LDTs collected in 2015–2019 (Colorado) and 2015–2021 (Virginia).[22] Table 1 provides a summary of the number of measurements by vehicle model year group, as well as an overview of testing conditions. Each model year group contains up to 3.2 million measurements per group of vehicles from a 5-year model year span, or

16 The database also contains measurements from the University of Denver; however, these data are not analyzed in this report as they represent less than 1% of measurements in the database.

17 Bernard, Dallmann, Tietge, Badshah, and German *Development and application of a United States real-world vehicle emissions database.*

18 Liuhanzi Yang, Ruoxi Wu, Yoann Bernard, Tim Dallmann, Uwe Tietge, Sunggi Shin, Il-woong Yang, Dongjun Ha, Beunsoo Park, Songjae Yang, and Jinyoung Song, *Remote Sensing of Motor Vehicle Emissions in Seoul*, (Washington, DC: ICCT, 2022), https://www.trueinitiative.org/media/792173/remote-sensing-seoul-true-paper.pdf; Yuche Chen, Ruixiao Sun, and Jens Borken-Kleefeld, "On-Road NOx and Smoke Emissions of Diesel Light Commercial Vehicles–Combining Remote Sensing Measurements from across Europe," *Environmental Science & Technology*, September 8, 2020, https://doi.org/10.1021/acs.est.9b07856.

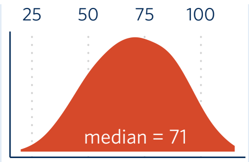
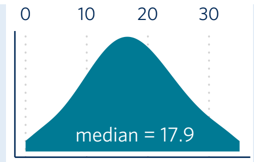
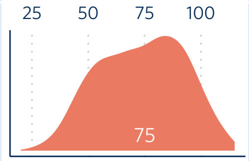
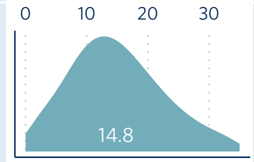
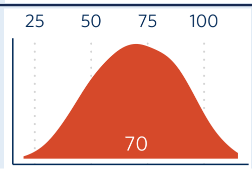
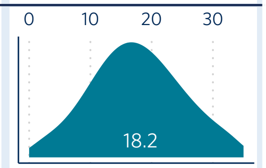
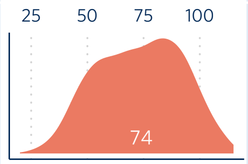
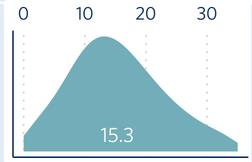
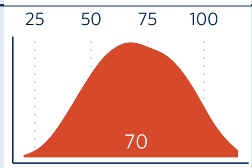
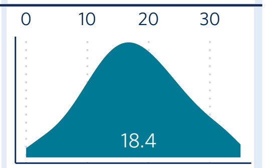
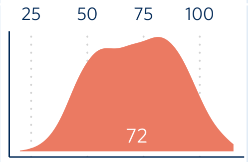
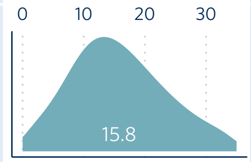
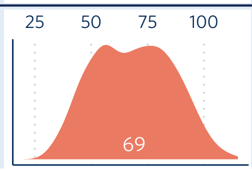
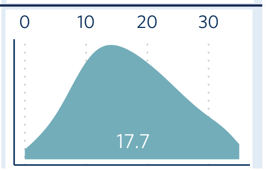
19 For the analysis of remote sensing data, LDVs are defined as passenger cars and car SUVs and LDTs are defined as pick-up trucks, minivans, and truck SUVs. See U.S. Environmental Protection Agency, "The 2022 EPA Automotive Trends Report."

20 Vehicle specific power is a surrogate for engine load calculated using speed, acceleration, and road slope. See Yoann Bernard, Uwe Tietge, John German, and Rachel Muncrief, *Determination of Real-World Emissions from Passenger Vehicles Using Remote Sensing Data,* (Washington, DC: ICCT, 2018), https://theicct.org/publication/determination-of-real-world-emissions-from-passenger-vehicles-using-remote-sensing-data/.

21 Negative values indicate that the tailpipe opacity measurement is less than the ambient opacity measurement. These limits are developed based on highest values observed under laboratory and point sampling testing in Europe.

22 The exact number of measurements is 3,753,638 LDV and 8,190,988 LDT from the Colorado data and 3,631,926 LDV and 3,208,286 LDT from the Virginia data.

Table 1. Summary of remote sensing measurements and testing conditions for gasoline light-duty vehicles and trucks by model year group

Model years	Average real-world CO_2 (g/mi)		Data source	Measurements		Ambient temperature (°F)	VSP (kW/ton)
	LDV	LDT		LDV	LDT		
2005–2009	369	509	CO	1,308,831	2,268,418		
			VA	882,501	612,401		
2010–2014	324	454	CO	1,678,118	3,230,139		
			VA	1,558,423	1,079,816		
2015–2019	299	418	CO	765,445	2,690,195		
			VA	1,132,377	1,393,144		
2020–2021	275	395	VA	58,625	122,925		

approximately 650,000 measurements per individual model year.

The measurement conditions are relatively consistent across all groups. The ambient temperatures include some implausible values above 110°F; however, the distributions are generally comparable. Some differences in VSP trends can be observed between model years 2020–2021 and earlier model years.

Within the Virginia dataset, 2020–2021 model year vehicles have the least number of measurements, as these vehicles were only measured in 2019–2021.[23] Slightly higher VSPs are observed for model years 2020–2021 compared to model years 2005–2019, likely

23 Very limited data on this model year group were collected in Colorado, as the most recent measurement year is 2019. Therefore, these model years are not shown for Colorado results in future sections of the report.

attributable to reduced traffic due to the COVID-19 pandemic; however, the difference is small enough that it is still appropriate to compare the 2020 and 2021 model year vehicles to earlier model year vehicles.

The remote sensing measurements were initially reported as fuel-specific emissions (g/kg fuel) and are converted to distance-specific emissions (g/miles travelled) for this analysis. This conversion effectively adjusts for improvements in fuel economy over time and allows for a more even comparison across individual model year groups. We follow methods previously developed by the TRUE Initiative and use data reported by EPA on average real-world CO_2 by model year for different vehicle classes to perform these conversions.[24] Table 1 shows the average real-world CO_2 emissions by vehicle model year group for the sample of vehicles analyzed in this study. Compared to the 2005–2009 model year group, newer 2020–2021 model year vehicles show a 22% (LDT) and 25% (LDV) reduction in real-world CO_2 emission rates, a change which reflects fleet-average improvements in fuel economy.

In this analysis, we assess the relative trends of PM emissions over time by analyzing the average UV smoke measurement across model years. The large dataset of nearly 19 million measurements helps to reduce the uncertainty associated with reduced accuracy of the UV smoke remote sensing measurement.

We also perform a more detailed analysis on the most common gasoline LDV and LDT vehicle models in the database to directly compare results from GDI and PFI vehicles. To determine the fuel injection method of the most common vehicle models in the remote sensing database, we use data from the U.S. Department of Energy, which contains detailed information on vehicle models by model year.[25] Each model year group in this analysis contains a minimum of 100 measurements. Finally, we conduct a supplemental analysis using data from EPA certification chassis dynamometer testing, a method of measuring PM with a higher accuracy compared to remote sensing. This additional evidence comparing GDI and PFI vehicle PM emissions is presented in the appendix.

24 Yoann Bernard, Tim Dallmann, Uwe Tietge, Huzeifa Badshah, and John German, *Emissions distribution by vehicle age and policy implications,* (Washington, DC: ICCT 2020), https://www.trueinitiative.org/media/791468/us-emissions-distributions.pdf

25 U.S. Department of Energy, "Fuel Economy Guide Datafile," (2012–2022), https://www.fueleconomy.gov/feg/download.shtml.

TRENDS IN UV SMOKE BY MODEL YEAR

This section presents the analysis of UV smoke measurements by vehicle model year. The analysis looks at distance-specific (g/mi) measurements, which are converted from fuel-specific values (g/kg fuel).

Figure 2 shows the trends in average distance-specific UV smoke by model year in terms of percent change since model year 2005. Results are presented separately for LDVs and LDTs and for the Colorado and Virginia datasets. We observe similar overall trends across each state dataset and for each vehicle type. In each case, we see the fastest rate of average UV smoke reductions from model years 2005 to 2010. This rate of reduction in UV smoke decreases and levels off from model years 2010 to 2015. For each data subgroup, average UV smoke levels begin to increase starting in model year 2015 and continue through model year 2020, the last model year considered for this analysis. Recent vehicles of model years 2018–2020 show similar UV smoke averages as model year 2005 vehicles.[26] These findings suggest that, at the fleet level, the trend of decreasing average PM emissions from gasoline vehicles has not been sustained over time and that progress has been nearly erased with newer model year vehicles.

The observed trend of increasing UV smoke with newer model years is not consistent with long-term fleet-average emission trends for other tailpipe pollutants. Figure 3 displays emission trends by model year for all pollutant measurements in the remote sensing data. For this figure, we show the combined data from light-duty vehicles and trucks from both the Colorado and Virginia datasets. The average CO, HC, and NO emissions in each model year show clear and consistent downward trends, and the average emissions of model year 2020 vehicles are between 66% and 86% lower than those of model year 2005 vehicles. These real-world trends are consistent with what would be expected with the implementation of more stringent tailpipe emission standards and improvements in engine and emissions control technology. These results contrast with the trend in UV smoke across model years, for which the fleet average declined only slightly before leveling off and then increasing with the newest model year vehicles.

26 The LDV 2019 model year average for Colorado is excluded from the figure due to the large 95% confidence interval with a range of nearly 30%.

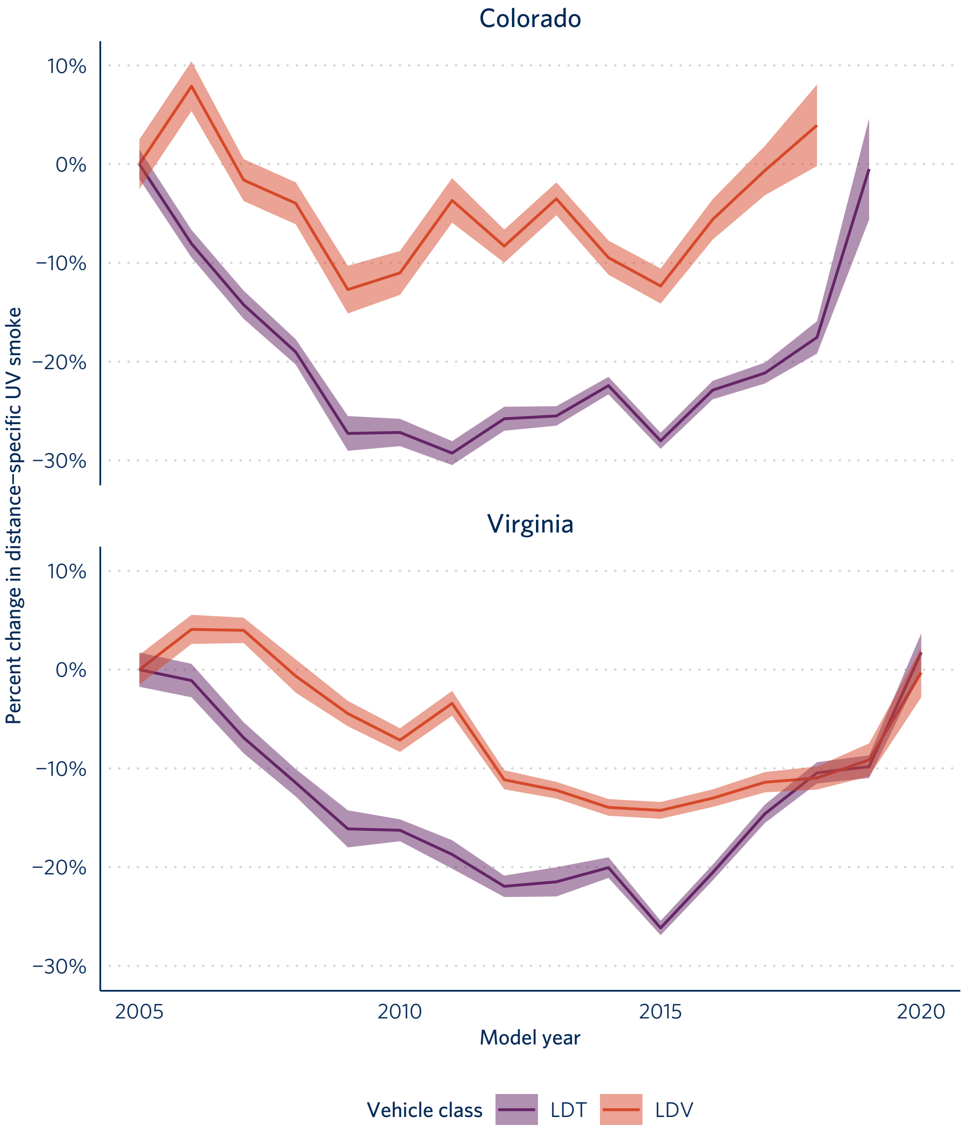


Figure 2. Percent change in distance-specific UV smoke by model year, compared to model year 2005. The shaded region shows the 95% confidence interval.

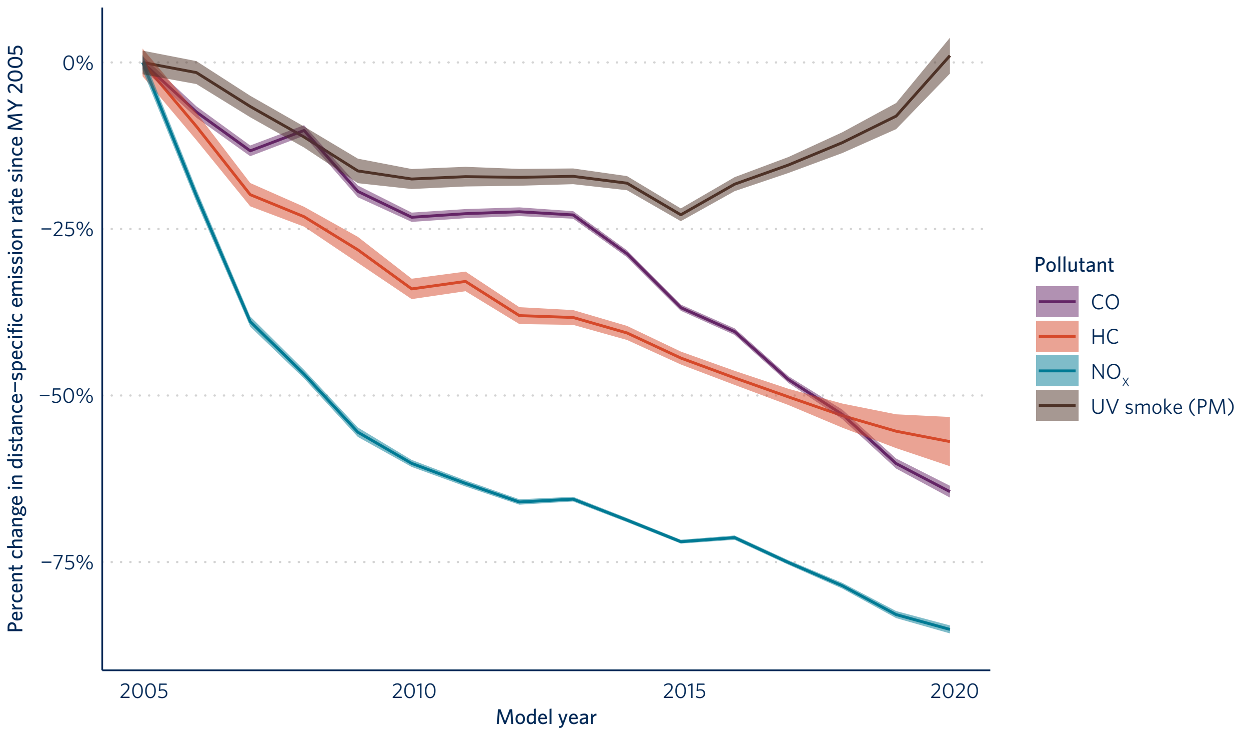


Figure 3. Percent change in distance-specific emissions for various pollutants by model year for LDV and LDT combined, compared to model year 2005. The shaded region shows the 95% confidence interval.

COMPARISON OF UV SMOKE ACROSS THE MOST POPULAR LDV AND LDT MODELS

To better understand the influence of GDI vehicle uptake on the observed increases in model year average UV smoke levels, we performed a more detailed analysis of the data from the most common vehicle models in the remote sensing datasets. We focus here on model year 2015–2020 vehicles, as this period corresponds with an increase in fleet-average UV smoke.

The most common models are determined based on the number of occurrences in the database. Vehicle models which rank in the top 30 in the Colorado or Virginia in terms of number of vehicles measured are included. Each of these models are assigned a corresponding fuel injection system from the U.S. Department of Energy database.[27] This assignment is done by model year, and an individual vehicle model may be split up into two or three different groups. For example, a vehicle model which used PFI for model years 2015–2017, a mix of PFI and GDI for model years 2018, and GDI for model years 2019–2020 would be split into three different groups: PFI, other/mixed, and GDI, respectively.[28] After grouping by fuel injection system, there are 53 model groups for LDVs and 51 model groups for LDTs.

Figure 4 shows the ratio of the UV smoke measurement to the fleet average and the 95% confidence intervals for each of the model groups for the most common LDV models, with the color corresponding to each of the fuel injection methods. Each group is assigned a numeric label for comparisons between the Colorado and Virginia trends.[29] Of the vehicle groups with above average emissions (ratio > 1.0), nearly all are GDI vehicles. Of the ten vehicle model groups showing UV smoke measurements above average with 95%

27 U.S. Department of Energy, "Fuel Economy Guide Datafile."

28 The label of "other/mixed" refers to groups that either contain both PFI and GDI vehicles or vehicles that use a combination of both port and direct injection methods.

29 The bars are arranged in descending order by the average UV smoke ratio across both the Colorado and Virginia datasets (ex. For model group 1, the average of 2.4 and 1.3). A few model groups are not included in the Colorado chart as they are recent model years (2020–2021) and thus are not available in the Colorado dataset, which includes measurements up to 2019.

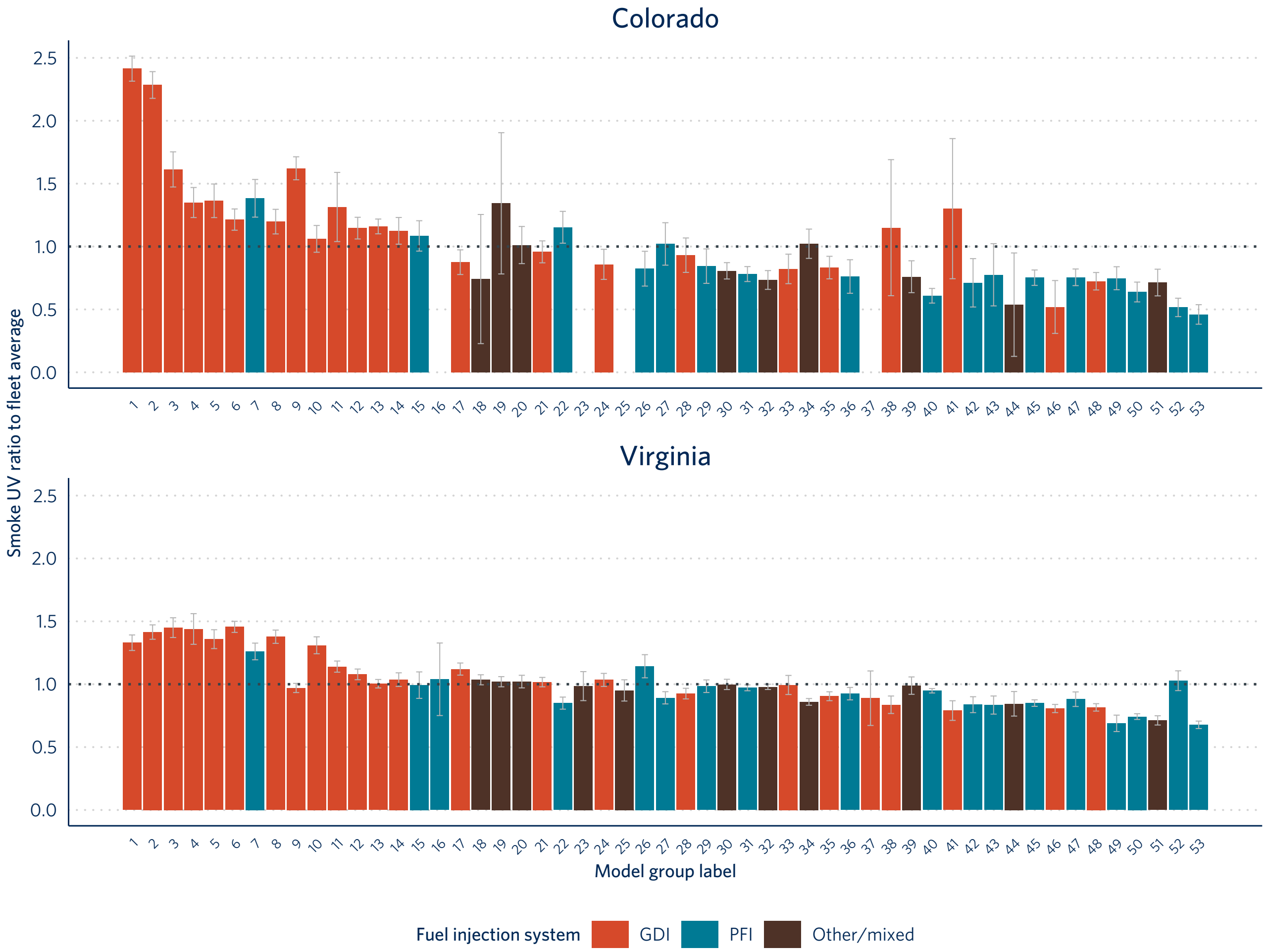


Figure 4. UV smoke comparison by vehicle model for the most popular LDV models, categorized by fuel injection system. The error bars show the 95% confidence interval.

confidence in both states' datasets, nine are GDI vehicle models.

The relative differences are more pronounced in the Colorado dataset compared to the Virginia dataset. For Colorado, the model groups show ratios of up to 2.5 compared to 1.5 for Virginia. It is unclear what the reason for this difference is; however, potential factors include ambient conditions such as altitude and driving conditions. Despite the differences in magnitude of the trends between the two datasets, the overall trend of higher UV smoke averages from GDI vehicles is consistent across both datasets.

Figure 5 displays the UV smoke comparison for the most popular LDT models. A similar trend can be seen, where the model groups with the highest averages are mostly GDI vehicles or a mix of GDI and PFI engines.

Of the ten vehicle model groups showing UV smoke measurements above average with 95% confidence in both states' datasets, five are GDI vehicle models and four are groups with a mix of GDI and PFI engines. Additionally, the groups showing UV smoke averages below the fleet average are mostly PFI vehicles. PFI vehicle models account for 13 of the 21 vehicle models with UV smoke measurements below average with 95% confidence. The vehicle models showing the lowest ratios, which are as low as to 0.36 (64% below the fleet average), are nearly all PFI vehicles.

The trend of higher PM emissions from GDI vehicles compared to PFI vehicles is also observed in official certification testing data. The appendix presents results from EPA certification testing, showing that average GDI vehicle PM emissions are higher than PFI vehicle PM emissions across all model years and

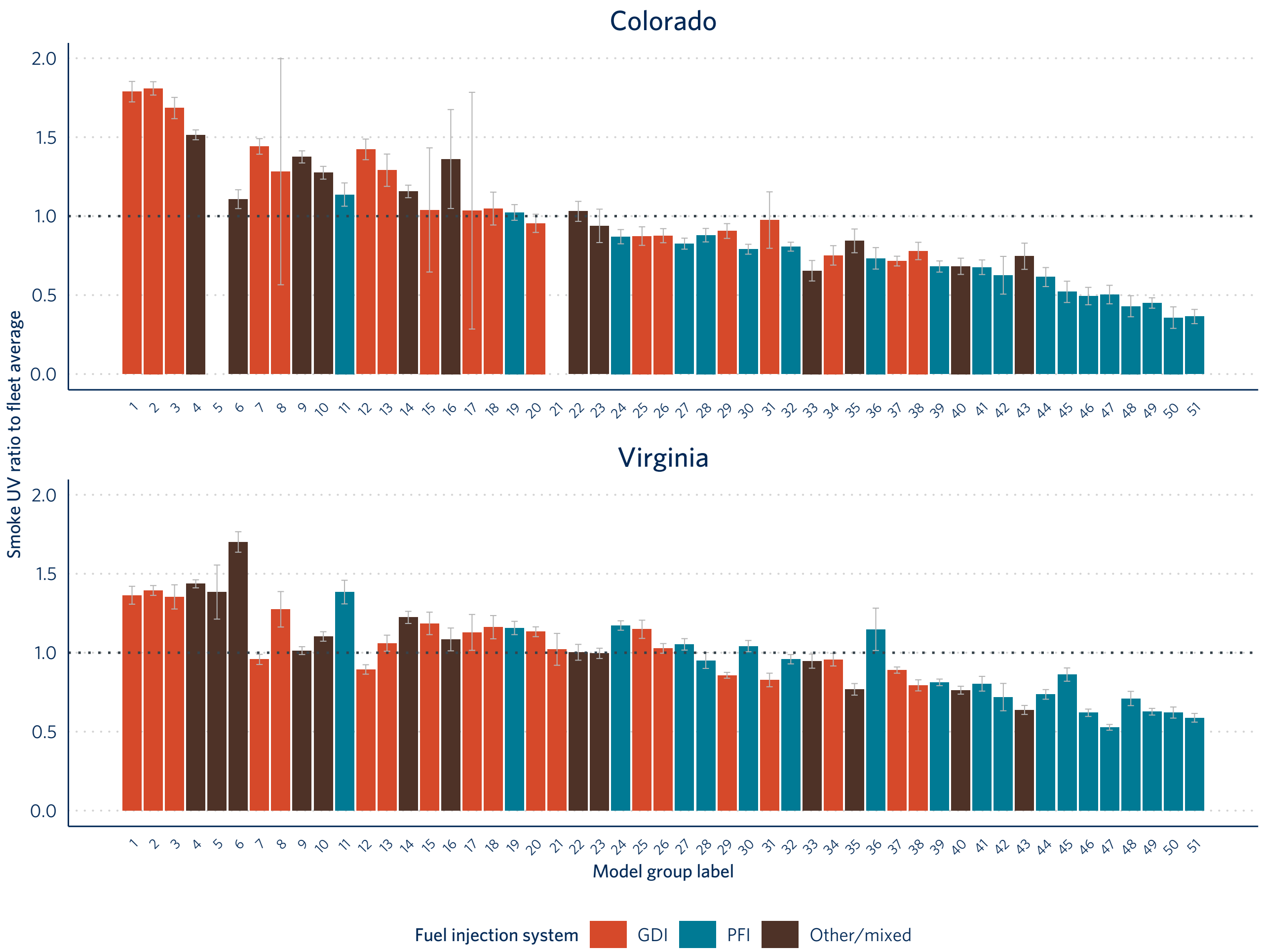


Figure 5. UV smoke comparison by vehicle model for the most popular LDT models, categorized by fuel injection system. The error bars show the 95% confidence interval.

for nearly all manufacturers. This analysis provides further evidence of the connection between the uptake of GDI vehicles and the increase of fleet-average UV smoke measurements.

POLICY IMPLICATIONS

Technologies to address gasoline tailpipe PM emissions are well established and widely used in other vehicle markets outside of the United States. The gasoline particulate filter (GPF) is an aftertreatment device which has been shown to significantly reduce PM emissions from GDI vehicles by 97%–100% compared to non-GPF equipped vehicles.[30] As the U.S. Tier 3 PM emission limits can be met without the application of GPFs, the technology is not widely used in the U.S. fleet.[31]

In contrast, stringent particulate standards in the European Union and China have led to the widespread application of GPFs. The regulations in the two regions pose both particle mass and particle number limits, effectively regulating both fine particulates ($PM_{2.5}$) and

30 Jiacheng Yang et al., "Gasoline Particulate Filters as an Effective Tool to Reduce Particulate and Polycyclic Aromatic Hydrocarbon Emissions from Gasoline Direct Injection (GDI) Vehicles: A Case Study with Two GDI Vehicles," *Environmental Science & Technology* 52, no. 5 (March 6, 2018): 3275–84, https://doi.org/10.1021/acs.est.7b05641.

31 DieselNet, "Gasoline Particulate Filters," 2021, https://dieselnet.com/tech/gasoline_particulate_filters.php.

ultrafine particulates, ($PM_{0.1}$).[32] Ultrafine particulates,, which are less than 100 nm in size, have been found to be even more dangerous to human health than $PM_{2.5,}$ as they can be inhaled deeper into the lungs, increasing the chances of the particles of entering the bloodstream.[33] Part of the motivation for the stringent particulate regulations in the European Union and China has been the uptake of GDI vehicles, which have been found to emit more ultrafine particulates down to a size of 23 nm and can emit even smaller particles (sub 23 nm).[34] GPFs have been proven to be an effective solution to reduce ultrafine particulate emissions from GDI vehicles to meet emission standards, thus reducing negative health impacts.[35]

According to EPA, the PM standard outlined in the proposed multipollutant rule for light- and medium-duty vehicles would require GPFs.[36] These devices would help to greatly reduce both fine and ultrafine particulates from gasoline light-duty vehicles and trucks to protect public health at an estimated manufacturing cost of $51–$166 per vehicle.[37] The adoption of GPFs in the U.S. vehicle fleet would help to counteract recent increases in PM emissions from gasoline vehicles.

CONCLUSION

This analysis of nearly 19 million remote sensing measurements investigates the connection between the uptake of GDI technology and long-term trends in real-world PM emissions. The trends over time for UV smoke, a proxy for PM emissions, are markedly different from those of other pollutants. While real-world data show continued decreases in fleet average CO, HC, and NO_X emissions with newer model years, UV smoke trends indicate that modest reductions between model year 2005 and 2015 vehicles have been virtually eliminated, with model year 2020 vehicles emitting roughly the same levels as model year 2005 vehicles.

This analysis also presents evidence of higher PM emissions from GDI vehicle models, indicating that the uptake of GDI engines in the United States is likely a main contributor to the recent rise in PM emissions.

Additional analyses are recommended to fully characterize the influence of the shift towards GDI engines on PM emissions from gasoline light-duty vehicles. This report presents analyses of remote sensing data to display fleet and model-level relative trends and summaries of certification data to display differences between GDI and PFI vehicles under official testing conditions. Future studies using other technologies to measure PM emissions of GDI and PFI vehicles under real-world driving conditions would provide more accurate quantifications of the differences in emissions performance between the two fuel injection methods. In addition, turbochargers, which are more common in GDI vehicles, and their impact on PM emissions should be studied.

This report presents evidence of rising gasoline light-duty vehicle and truck PM emissions in the United States, highlighting the importance of strong PM emission standards to address the environmental justice and health impacts associated with gasoline vehicle emissions. EPA's proposed multipollutant rule would greatly reduce PM emissions from gasoline vehicles by likely requiring the use of GPFs, which would help to greatly reduce fine and ultrafine particulate matter emissions. Introducing this more stringent PM standard quickly would help counteract the trend of higher PM emissions from recent gasoline vehicles.

32 Felix Leach, Elana Chapman, Je J. Jetter, Lauretta Rubino, Earl D. Christensen, Peter C. St. John, Gina M. Fioroni, and Robert L. McCormick, "A Review and Perspective on Particulate Matter Indices Linking Fuel Composition to Particulate Emissions from Gasoline Engines," *SAE International Journal of Fuels and Lubricants* 15, no. 1 (October 8, 2021): 3–28, https://doi.org/10.4271/04-15-01-0001.

33 Dean E. Schraufnagel, "The Health Effects of Ultrafine Particles," *Experimental & Molecular Medicine* 52, no. 3 (March 2020): 311–17, https://doi.org/10.1038/s12276-020-0403-3.

34 Barouch Giechaskiel, Urbano Manfredi, and Giorgio Martini, "Engine Exhaust Solid Sub-23 Nm Particles: I. Literature Survey," *SAE International Journal of Fuels and Lubricants* 7, no. 3 (October 13, 2014): 950–64, https://doi.org/10.4271/2014-01-2834.

35 Yang et al., "Gasoline Particulate Filters as an Effective Tool to Reduce Particulate and Polycyclic Aromatic Hydrocarbon Emissions from Gasoline Direct Injection (GDI) Vehicles"; Leach et al., "A Review and Perspective on Particulate Matter Indices Linking Fuel Composition to Particulate Emissions from Gasoline Engines."

36 U.S. Environmental Protection Agency, "Multi-Pollutant Emissions Standards for Model Years 2027 and Later Light-Duty and Medium-Duty Vehicles: Draft Regulatory Impact Analysis," April 2023, https://www.epa.gov/system/files/documents/2023-04/420d23003.pdf.

37 U.S. Environmental Protection Agency, "Multi-Pollutant Emissions Standards for Model Years 2027 and Later Light-Duty and Medium-Duty Vehicles: Draft Regulatory Impact Analysis."

APPENDIX: COMPARISON OF GDI AND PFI VEHICLE PM EMISSIONS FROM LABORATORY CERTIFICATION TESTING

To compare the PM emissions of GDI and PFI vehicles, we use the EPA's certification database and the U.S. Department of Energy's (DOE) fuel economy test data.[38] EPA's certification data includes the chassis dynamometer-based PM emissions for specific drive cycles that are used for testing compliance to the emission standards for each manufacturer and model year. Information on whether a vehicle model is GDI or PFI is acquired from the DOE's fuel economy test data. These two databases were joined by vehicle identifiers referred to as "smog rating test group" in DOE data and "certified test group" in EPA data.

We evaluate the PM emissions from model years 2013–2023 as reported in the EPA's certification data. For certification, vehicles are tested under two different drive cycles, Federal Test Procedure (FTP) and a supplemental FTP test, US06, which captures more aggressive driving and stop-and-go driving conditions.[39] The EPA database contains PM emissions records for nearly 5,000 unique measurements reported for model years 2013–2023 for combinations of various features such as vehicle make, model, fuel type, level of emissions standards, and test cycle. We found a match for 4,053 of the 4,874 vehicles (83%) reported in EPA database with those from the DOE data for model years 2013–2023. GDI vehicles make up two-thirds of these 4,053 measurements.

Figure A1 shows the trends of average PM emissions for GDI and PFI vehicles on the FTP cycle. PM emissions from GDI vehicles have been reducing over the years; however, they are still significantly higher than the PFIs on the FTP cycle. For 2023 model year vehicles, GDIs emit, on average, about three times more than the PFIs on the FTP cycle.

The differences are not nearly as significant on the US06 cycle (Figure A1). For 2023 model year vehicles, GDIs average only 7% higher emissions than PFIs. On both FTP and US06 cycles, the trajectory of average PM emissions for GDI vehicles flattens over the last few years, suggesting that PM emissions from GDIs likely will not substantially reduce further under the current Tier 3 emissions standard.

Table A1 shows a more detailed analysis by manufacturer of PM emissions for GDI and PFI vehicles averaged over the last 5 years (2019–2023) on FTP and US06 cycles. Blank cells indicate a given manufacturer has 0% sales for the corresponding technology. Almost all manufacturers that have sales for both GDI and PFI vehicles have significantly higher PM emissions from GDIs than PFIs.

Table A1. Average PM emissions (mg/mile) for GDI and non-GDI vehicles by manufacturer for 2019–2023 model year vehicles

	FTP cycle Phased-in Tier 3 limit = 3 mg/mile		US06 cycle Phased-in Tier 3 limit = 6 mg/mile	
Manufacturer	**GDI**	**PFI**	**GDI**	**PFI**
A	1.53	0.26	1.53	1.32
B	1.14	0.41	1.49	0.64
C	1.00	0.23	1.63	1.92
D	0.99	0.18	2.26	1.55
E	0.76	0.47	2.19	0.94
F	0.72	0.26	1.47	1.39
G	1.50		1.05	
H	0.94		1.63	
I	0.81		1.70	
J	0.80		1.31	
K	0.51		1.51	
L		0.29		1.47

38 U.S. Environmental Protection Agency, "Annual Certification Data for Vehicles, Engines, and Equipment," Data and Tools, November 8, 2017, https://www.epa.gov/compliance-and-fuel-economy-data/annual-certification-data-vehicles-engines-and-equipment; U.S. Department of Energy, "Fuel Economy Guide Datafile."https://www.fueleconomy.gov/feg/download.shtml

39 U.S. Environmental Protection Agency, "EPA Sets Tier 3 Tailpipe and Evaporative Emission and Vehicle Fuel Standards."

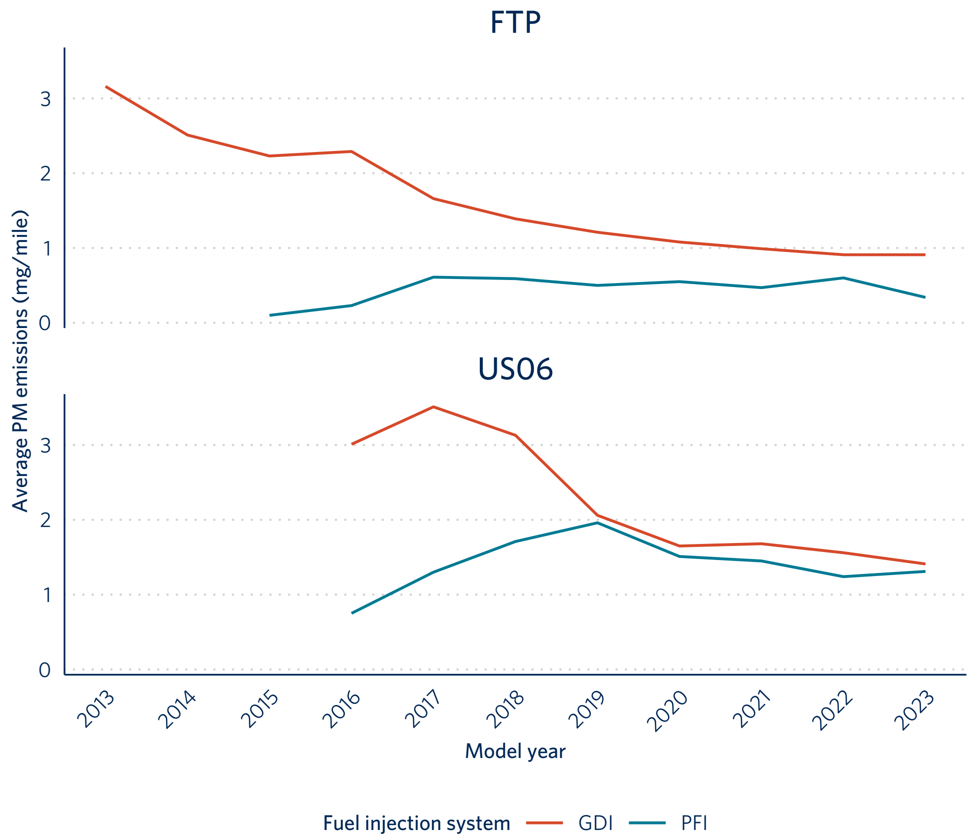


Figure A1. Trend of average PM emissions for U.S. LDVs based on EPA certification database for GDI and PFI vehicles under FTP and US06 regulatory cycles

TRUE THE REAL URBAN EMISSIONS INITIATIVE

FIA FOUNDATION icct THE INTERNATIONAL COUNCIL ON CLEAN TRANSPORTATION

TO FIND OUT MORE

For details on the TRUE U.S. remote sensing database and related questions, contact **Michelle Meyer, m.meyer@theicct.org**.

For more information on TRUE, visit **www.trueinitiative.org**.