THE REAL URBAN EMISSIONS INITIATIVE

Impacts of the Paris low-emission zone and implications for other cities

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THE TRUE INITIATIVE

Studies have documented significant and growing discrepancies between the amount of nitrogen oxides (NO_x) emissions measured in diesel vehicle exhaust during type-approval tests and the amount that the vehicle emits in "real-world" operation—on the road, in normal driving. Excess real-world emissions are an important issue, particularly in Europe where dieselization of the light-duty vehicle fleet is much higher than in other global regions. Poor real-world NO_x emission control has contributed to persistent air quality problems in many European cities and has adversely impacted public health.

FIA Foundation, the International Council on Clean Transportation (ICCT), C40 Cities, Global NCAP, and Transport and Environment have established The Real Urban Emissions (TRUE) Initiative. The TRUE initiative seeks to supply cities with data regarding the real-world emissions of their vehicle fleets and equip them with technical information that can be used for strategic decision making.

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INTRODUCTION

Road transport exhaust emissions have been linked to approximately 39,000[1] premature deaths in the European Union (EU) annually in 2015. Among EU member states, France suffered the third highest health impacts from road transport exhaust, after Germany and Italy.[2] These health impacts are particularly severe in densely populated areas with high volumes of motorized traffic. Paris is one such area: In 2015, transport exhaust emissions accounted for about one-third of fine particulate matter and ozone-related premature deaths. In other words, transport exhaust emissions were associated with a mortality rate of 11 citizens per 100,000 population in Paris. An estimated 71% of this transportation health burden is attributed to on-road diesel vehicles.[3]

Cities in Europe and around the world have adopted a variety of urban vehicle access regulations with the objective of reducing traffic-related air pollution and congestion.[4] One kind of urban vehicle access regulation, low-emission zones (LEZs), limits vehicle access to a defined geographic area e.g., a city center,

HOW DO LOW EMISSION ZONES OPERATE?

Low emission zones (LEZs) may apply restrictions to light-duty vehicles, heavy-duty vehicles, motorcycles, or any combination of vehicle types. Most LEZs operate 24 hours a day, 365 days a year (e.g., Berlin, Stuttgart, Amsterdam, Brussels), whereas others operate only on certain days and at certain times (e.g., Paris). LEZs are enforced either with camera systems using license plate recognition (e.g., Amsterdam, Brussels) or manually using windshield stickers (e.g. Berlin, Stuttgart, Paris).

The stringency of current LEZ requirements varies substantially among cities as of this writing.[I] Requirements can vary in terms of vehicle types allowed, applicable emission standards, times of restrictions, or charges for noncompliant vehicles to enter the zone. In Brussels, the LEZ covers the entire capital region territory, regulating access for passenger cars, vans, minibuses, and coaches. Depending on the fuel type, these vehicles either must meet at least Euro 2 (petrol, light petroleum gas [LPG], and compressed natural gas [CNG] vehicles) or at least Euro 4 (diesel vehicles).[II] In Madrid's inner-city LEZ, only battery-electric vehicles (BEVs), range-extended electric vehicles (REEVs), plug-in hybrid-electric vehicles (PHEVs) with a minimum range autonomy of 40 km, and hydrogen fuel cell vehicles (FCVs) can drive and park; cars, vans, and motorcycles that do not meet these technology requirements are limited in terms of access time and parking.[III] London operates a citywide LEZ for lorries and other vehicles over 3.5 tons and a separate Ultra Low Emission Zone (ULEZ) in the city center for all vehicles. Drivers of a car or van, for example, who wish to enter the ULEZ need to meet the minimum Euro 4 standard for petrol and Euro 6 for diesel vehicles. Noncompliant vehicles must pay a daily fee of £12.50.[IV]

I Sandra Wappelhorst and Rachel Muncrief, *How can real-world vehicle emissions data help cities to become zero-emission: Some evidence from Europe*, Policy Dialogue 1, (London: *TRUE – The Real Urban Emissions Initiative,* May 2019), https://www.trueinitiative.org/media/749323/true-policy-dialogue-paper-1.pdf

II City of Brussels, Low Emission Zone: new bans from 2019 (2019), https://www.brussel.be/lage-emissie-zone-nieuw-verbod-vanaf-2020

III Madrid City Council, Central Madrid General Information [in Spanish] (n.d.), https://www.madrid.es/portales/munimadrid/es/Inicio/Movilidad-y-transportes/Madrid-Central-Zona-de-Bajas-Emisiones/Informacion-general/Madrid-Central-Informacion-General/?vgnextfmt=default&vgnextoid=a67cda4581f64610VgnVCM2000001f4a900aRCRD&vgnextchannel=088e96d2742f6610VgnVCM1000001d4a900aRCRD

IV Transport for London, Ultra Low Emission Zone (n.d), https://tfl.gov.uk/modes/driving/ultra-low-emission-zone

1 Estimate is 28,000 to 50,000 at 95% confidence interval reflecting uncertainty in the concentration-response function.

2 Susan C. Anenberg, Joshua Miller, Daven K. Henze, Ray Minjares, and Pattanun Achakulwisut, "The Global Burden of Transportation Tailpipe Emissions on Air Pollution-Related Mortality in 2010 and 2015," *Environmental Research Letters* 14, no. 9 (September 2019): 094012, https://doi.org/10.1088/1748-9326/ab35fc.

3 Susan Anenberg, Joshua Miller, Daven Henze, and Ray Minjares, *Health impacts of air pollution from transportation sources in Paris* (2019), Fact Sheet: Europe, https://theicct.org/sites/default/files/publications/Paris_pollution_heath_issues_transport_factsheet_20190226.pdf

4 Sandra Wappelhorst and Rachel Muncrief, *How can real-world vehicle emissions data help cities to become zero-emission: Some evidence from Europe*, Policy Dialogue 1 (London: *TRUE – The Real Urban Emissions Initiative*, May 2019), https://www.trueinitiative.org/media/749323/true-policy-dialogue-paper-1.pdf

city, or metropolitan area) based on vehicle emissions performance or certification level. The primary aim of LEZs is to reduce exposure to traffic-related air pollution, particularly fine particles ($PM_{2.5}$), nitrogen dioxide (NO_2), and precursors to secondary $PM_{2.5}$ and ozone (O_3). To date, roughly 265 European cities have adopted some form of LEZs,[5] however definitions and policy designs vary among countries and cities. Common criteria for designing a LEZ include an implementation schedule, the geographic boundary, affected vehicle types, minimum emissions performance or certification criteria, terms of access such as usage charges for noncompliant vehicles or bans with penalties, operating times, exempted vehicle categories, and enforcement methods.

Most LEZs have progressively tightened their requirements over time and are expected to continue to do so. This includes tighter rules in terms of emission standards, the extension of the regulated area, and more vehicle types being affected by the LEZ. In Milan, restrictions for certain petrol and diesel vehicles entering the city's LEZ were amended twice in 2019. Through 2030, access regulations will be further tightened based on vehicle type, engine type, and emission standard every two or three years.[6] Brussels tightened access criteria for its LEZ in January 2020 with further changes planned for 2022 and 2025.[7] London's ULEZ regulations may maintain the same emissions certification requirements over the next several years but the zone will be expanded by 18-fold from the city center to the inner-London area starting in October 2021.

There is some evidence available regarding the effectiveness of urban vehicle access regulations in reducing the concentration of harmful air pollution. Model estimates for London's ULEZ, introduced in April 2019, show that between July and September 2019, NO_x emissions from road transport were reduced by 31% (200 tons), $PM_{2.5}$ emissions by 15% (5 tons), and CO_2 emissions by 4% (9,800 tons).[8] Air quality measurements obtained from 24 stations in Madrid indicate that after the introduction of the inner-city LEZ in November 2018, average annual NO_2 emissions in 2019 were 10% lower compared to the annual average between 2010 and 2018. The highest impact was recorded at a measuring station in the city center, where NO_2 emissions were reduced by 22%.[9] After the introduction of Brussel's LEZ in January 2018, estimates based on camera data show that between a representative week in June and a representative week in December 2018, NO_x emissions from cars decreased by 4.7% and $PM_{2.5}$ emissions by 6.4%. The evaluation of the LEZ indicates that reasons for the reduction of pollutant emissions include a reduction in traffic and a decrease in the number of older, more polluting, noncompliant vehicles.[10]

This paper focuses on the LEZ in Paris, which came into force in September 2015, and evaluates the potential emissions benefit of the LEZ through 2030, focusing on the NO_x emissions of passenger cars. Considering the severity of Paris' present air quality challenges and the draft status of the LEZ schedule for the upcoming years, the emissions impacts of either adhering to or modifying this schedule are pertinent both for policymakers and the inhabitants of Paris. Therefore, the implementation of potential tightened restrictions of the LEZ is also analyzed as part of this paper. The paper concludes with a discussion of the implications of these estimates for the timing and stringency of the Paris LEZ and can serve as a blueprint for the design of LEZs in other cities in Europe and globally.

5 Transport & Environment, *Two-thirds of EU citizens support city bans to tackle air pollution – poll* (30 October 2018), https://www.transportenvironment.org/press/two-thirds-eu-citizens-support-city-bans-tackle-air-pollution-%E2%80%93-poll

6 Municipality of Milan, Area B: vehicles can not enter (2020), https://www.comune.milano.it/aree-tematiche/mobilita/area-b/area-b-veicoli-che-non-possono-entrare

7 Brussels, In practice: everything you need to know about the LEZ in the Brussels-Capital Region (n.d.), https://lez.brussels/mytax/en/practical?tab=Agenda

8 Mayor of London, Central London Low Emission Zone – Six month report (October 2019), https://www.london.gov.uk/sites/default/files/ulez_six_month_evaluation_report_oct19.pdf

9 Ecologistas en Acción de Madrid, *Balance del efecto de Madrid Central sobre la calidad del aire de Madrid en 2019 (Balance of the effect of Madrid Central on air quality in Madrid in 2019)* (9 January 2020), https://docs.google.com/viewerng/viewer?url=https://www.ecologistasenaccion.org/wp-content/uploads/2019/11/balance-2019-madrid-central.pdf

10 Bruxelles Environment, *Evaluation de la zone de basses emissions, rapport 2018 (Evaluation of the Low Emission Zone, Report 2018).* https://www.lez.brussels/medias/rapp-2018-lez-fr-def-2019-12-04.pdf?context=bWFzdGVyfHJvb3R8OTIxNzE3fGFwcGxpY2F0aW9uL3BkZnxoZjkvaDZkLzg4MDIxNzQzMDQyODYucGRmfGEyOTJhYzQzNTI4ZWJhYjE5ZTliNTdhMTdiODEyMjFjYTY5MjJhMDgzYzBhODU0NjA4OTA3NDQ1YzAzOWYxMTQ

EMISSIONS IMPACT OF THE PARIS LEZ

BACKGROUND ON LEZS IN FRANCE

On June 21, 2016, France introduced a national air quality certificate, CRIT'Air, which applies to all on-road vehicle types. The aim of this certification is to identify a vehicle's emissions levels and to, in some cases, restrict access to some locations in order to improve air quality in cities. The CRIT'Air certificate defines five classes based on vehicle type, fuel type, and emission standard certification.[11] The CRIT'Air classes for passenger cars are shown in Table 1. As of March 2020, diesel passenger cars cannot qualify for the CRIT'Air 1 class.[12] Passenger cars certified to Euro 1 and earlier cannot obtain a CRIT'Air certificate. Vehicle operators are required to obtain a CRIT'Air sticker and display it on their vehicle's windshield window in order to legally enter an area that applies access restrictions, such as the City of Paris, the Greater Paris region, or the cities of Lyon, Toulouse, and Strasbourg.

Paris was the first city in France to introduce a LEZ. The Paris LEZ covers the Ville de Paris municipality and excludes the Boulevard Périphérique. The zone's aims were to improve air quality, reduce noise, and reduce traffic congestion. The LEZ came into force in September 2015, initially limited access of heavy-duty vehicles to only those registered on or after October 1, 2001, and was effective daily from 8 a.m. to 8 p.m.[13] Since 2016, the criteria for the Paris LEZ have progressively tightened to limit access of all vehicle types based on their national CRIT'Air classification (see Table 2). Beginning July 1, 2016, the LEZ limited access to vehicles with a CRIT'Air classification (Phase 1) on weekdays from 8 a.m. to 8 p.m. After July 1, 2017, the LEZ required vehicles to meet at least CRIT'Air 4 during the same hours (Phase 2). Since July 1, 2019, the LEZ

Table 1. Classification of passenger cars for the CRIT'Air air quality certificate.

CRIT'Air Class	Sticker	Eligible cars
Green		• **Battery-electric vehicles** • **Hydrogen fuel cell vehicles**
1		• **Gas-powered vehicles** including liquified petroleum gas vehicles (LPGs) and compressed natural gas vehicles (CNGs) • **Plug-in hybrid-electric vehicles** (PHEVs, petrol and diesel) • **Petrol and hybrids Euro 5 and 6**
2		• **Petrol and hybrids Euro 4** • **Diesel Euro 5 and 6**
3		• **Petrol and hybrids Euro 2 and 3** • **Diesel Euro 4**
4		• **Diesel Euro 3**
5		• **Diesel Euro 2**
Unclassified	No sticker	• **Petrol and diesel Euro 1 and earlier**

Note: Ministère de la Transition Ecologique et Solidaire, *Vehicle classification table* (27 September 2019), https://www.certificat-air.gouv.fr/docs/tableaux_classement.pdf

11 Ministère de la Transition Ecologique et Solidaire, Obtaining the Air Quality Certificate (27 September 2019), https://www.certificat-air.gouv.fr/en/

12 Plug-in hybrids receive a Crit'Air 1 certificate independent of their category, emission standard, and fuel type, as of November 2019. There is no diesel plug-in hybrid model available for sale.

13 Paris, How Paris fights against air pollution [in French] (27 September 2019), https://www.paris.fr/pages/paris-lutte-contre-la-pollution-de-l-air-4308

Table 2. Draft implementation schedule of the LEZ in the City of Paris and Greater Paris.

	Phase 1 All vehicles need at least CRIT'Air 5 certificate	Phase 2 All vehicles need at least CRIT'Air 4 certificate	Phase 3 All vehicles need at least CRIT'Air 3 certificate	Phase 4 All vehicles need at least CRIT'Air 2 certificate	Phase 5 All vehicles need at least CRIT'Air 1 certificate	Phase 6 All vehicles need a green CRIT'Air certificate
City of Paris	July 1, 2016	July 1, 2017	July 1, 2019	2022[a]	2024[a]	2030[a]
Greater Paris	-	July 1, 2019	January 1, 2021	July 2022	January 2024	2030[a]

[a] Phases 4–6 for the City of Paris and Phase 6 for Greater Paris have draft implementation years, but the dates have not yet been announced.

Notes: Paris, *The Low Emission Zone (ZFE) to fight against air pollution* [in French] (27 September 2019), https://www.paris.fr/pages/nouvelle-etape-crit-air-des-le-1er-juillet-2017-4834

Metropolis of Greater Paris, *Breathe better to live better* [in French] (27 September 2019), https://www.zonefaiblesemissionsmetropolitaine.fr/

requires vehicles to meet at least CRIT'Air 3 to enter the City of Paris; to enter the larger Greater Paris area, vehicles need to meet at least CRIT'Air 4 (Phase 3). The requirements of the LEZ will be tightened from 2020 to 2030, with Greater Paris scheduled to be aligned with the City of Paris in January 2021. The long-term goal for the LEZ is to grant access only to vehicles with a green CRIT'Air certificate by 2030 (Phase 6).[14]

POTENTIAL EMISSIONS BENEFITS OF THE PARIS LEZ

If the City of Paris and the Greater Paris region adhere to the draft schedule for tightening the LEZ through 2030, the LEZ could become one of the most impactful local-level policies to curb traffic-related air pollution in Paris. In particular, permitting only vehicles with a green CRIT'Air certificate to enter the zone by 2030 would necessitate a transition from conventional vehicles to a combination of electric-drive vehicles, rail, and non-motorized transport modes.

METHODS

In this paper, we evaluate the potential emissions reduction benefit of the Paris LEZ, starting from its inception and continuing through 2024, when vehicles will need at least a CRIT'Air 1 sticker to enter the zone (see Table 2). Although the LEZ applies to all on-road vehicles and restricts the emissions of multiple pollutants, this initial analysis focuses on its impact on fleet-average NO_x emission factors of passenger cars, which are the primary source of NO_x emissions in Paris's Ile-de-France region.[15]

This analysis incorporates the disparity between laboratory limits and on-road performance by employing distance-specific NO_x emission factors by fuel type and Euro standards for passenger cars measured in Paris in summer 2018. To reflect the uncertainty in associating vehicle age to a certain emission standard, we present an "optimistic" and a "pessimistic" case as detailed in Figure 1. To model the effects of natural fleet turnover, we assume a constant vehicle age distribution derived from vehicle counts conducted in 2014, 2016, and 2018. The progression of fleet-average passenger car NO_x emission factors in the City of Paris is estimated both with and without the LEZ phases. In Paris, traffic management since the 2000s has resulted in an overall 31% decrease in road traffic (2001–2015).[16] In addition, some cities have reported that their LEZs also reduced traffic, for example by encouraging public transit ridership.[17] This paper does not investigate potential changes in the total number of vehicles accessing the city due to the LEZ; we instead focus on the potential effects on passenger car fleet composition and average emissions per kilometer traveled.

Given the observed influence of ambient temperature on NO_x emission factors, we report separate estimates

14 European Commission, *Urban access regulations in Paris* (27 September 2019), https://urbanaccessregulations.eu/countries-mainmenu-147/france/paris

15 Airparif, *Bilan des émissions atmosphériques en Ile-de-France* (Assessment of atmospheric emissions in Ile-de-France) (March 2019), https://www.airparif.asso.fr/_pdf/publications/inventaire_emissions_idf_2015_20190329.pdf

16 APUR, *"L'amélioration de la qualité de l'air en lien avec la baisse du trafic routier"* (Improving air quality in connection with the decline in road traffic - Contribution to the situation in Paris) (September 2019), https://www.apur.org/fr/nos-travaux/amelioration-qualite-air-lien-baisse-trafic-routier-contribution-situation-paris

17 Mayor of London, Central London Low Emission Zone – Six month report (October 2019), https://www.london.gov.uk/sites/default/files/ulez_six_month_evaluation_report_oct19.pdf

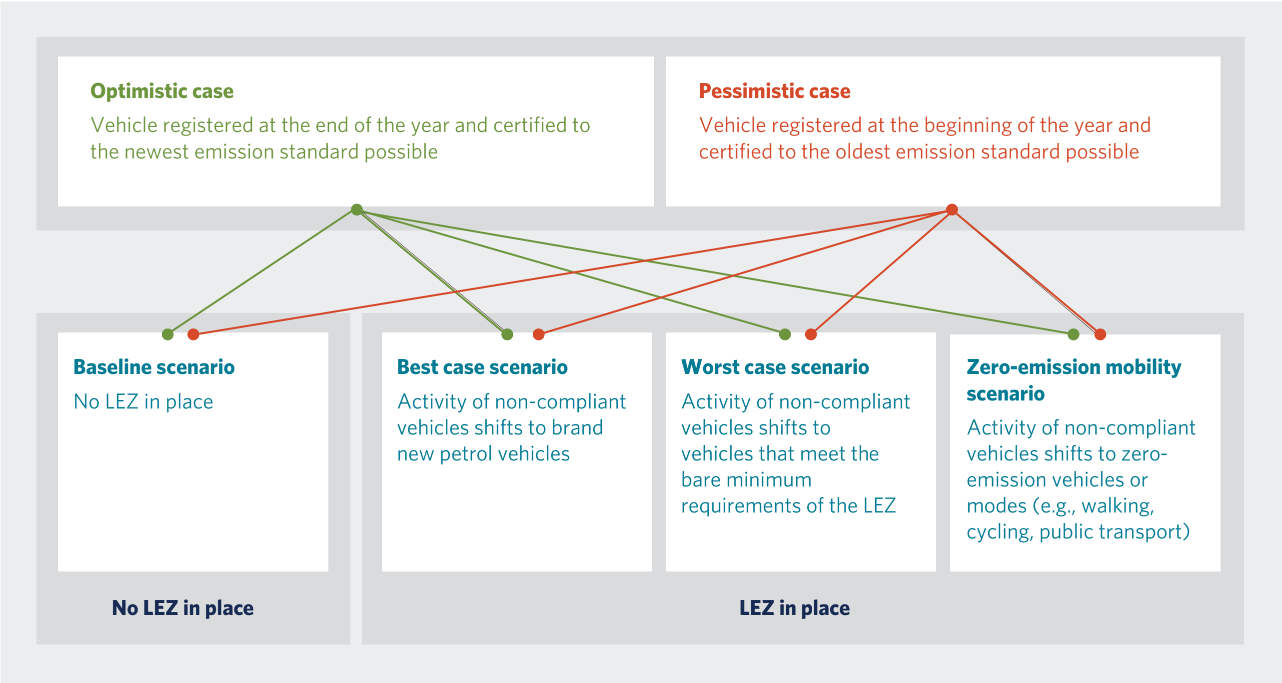

Figure 1: Overview of vehicle registration and consumer-response hypotheses used to model various scenarios of the LEZ's benefits.

for the hottest and coldest six months of each year. We also evaluate worst case and best case scenarios for shifts in passenger car activity by fuel type and emission control level to comply with the LEZ requirements. The worst case assumes that activity of noncompliant vehicles shifts to vehicles that meet the bare minimum requirements of the LEZ, whereas the best case assumes that activity of noncompliant vehicles shifts to brand new vehicles. In the final scenario, we assess the benefits of replacing noncompliant vehicles with zero-emission vehicles or modes.

PASSENGER CAR NO_x EMISSION FACTORS FOR THE HOTTEST SIX MONTHS OF THE YEAR

To measure the real-world emissions of vehicles in Paris, The Real Urban Emissions (TRUE) initiative carried out a 3-week remote-sensing testing campaign in the summer of 2018.[18] Two instrument units were set up within the Paris LEZ zone to measure vehicle exhaust emissions using a light-detector spectrometry technique. The study obtained more than 180,000 valid measurements with matching vehicle information, reflecting measurements of more than 130,000 unique vehicles. Passenger cars accounted for 72% of total records, and two-thirds of passenger car records were for diesel vehicles. Figure 2 shows the estimated average distance-specific NO_x emissions (mg/km) by fuel type and Euro standard for passenger cars measured during the campaign. Results confirm that diesel passenger cars exhibit high real-world NO_x emissions several times above their type-approval limits and systemically higher than petrol vehicles at equivalent Euro standards. These results were used to represent emission factors over the hottest six-month period of the year (May to October). Adjustment factors were developed later in this paper for the coldest six-month period (November to April).

For this analysis, we supplemented the results of the Paris campaign with estimated emission factors for Euro 1, Euro 6d-TEMP, and Euro 6d diesel and petrol passenger cars, as summarized in Table 3. For Euro 1, the Paris campaign did not measure enough of these vehicles to allow the calculation of distance-specific emission factors. These vehicles stopped being sold in Europe in 1997 and represented less than 0.02% of total passenger car measurements in the Paris campaign. The Euro 1 emission factors applied in this analysis are based on previous remote-sensing studies and assume no further emission deterioration.[19] Similarly, the Paris campaign captured only a small number of 6d-TEMP vehicles because these vehicles are relatively new

18 Tim Dallmann, Yoann Bernard, Uwe Tietge, and Rachel Muncrief, *Remote Sensing of Motor Vehicle Emissions in Paris* (September 2019), https://theicct.org/publications/on-road-emissions-paris-201909

19 Yoann Bernard, Uwe Tietge, John German, and Rachel Muncrief, *Determination of Real-World Emissions from Passenger Vehicles Using Remote Sensing Data* (June 2018), https://theicct.org/publications/real-world-emissions-using-remote-sensing-data

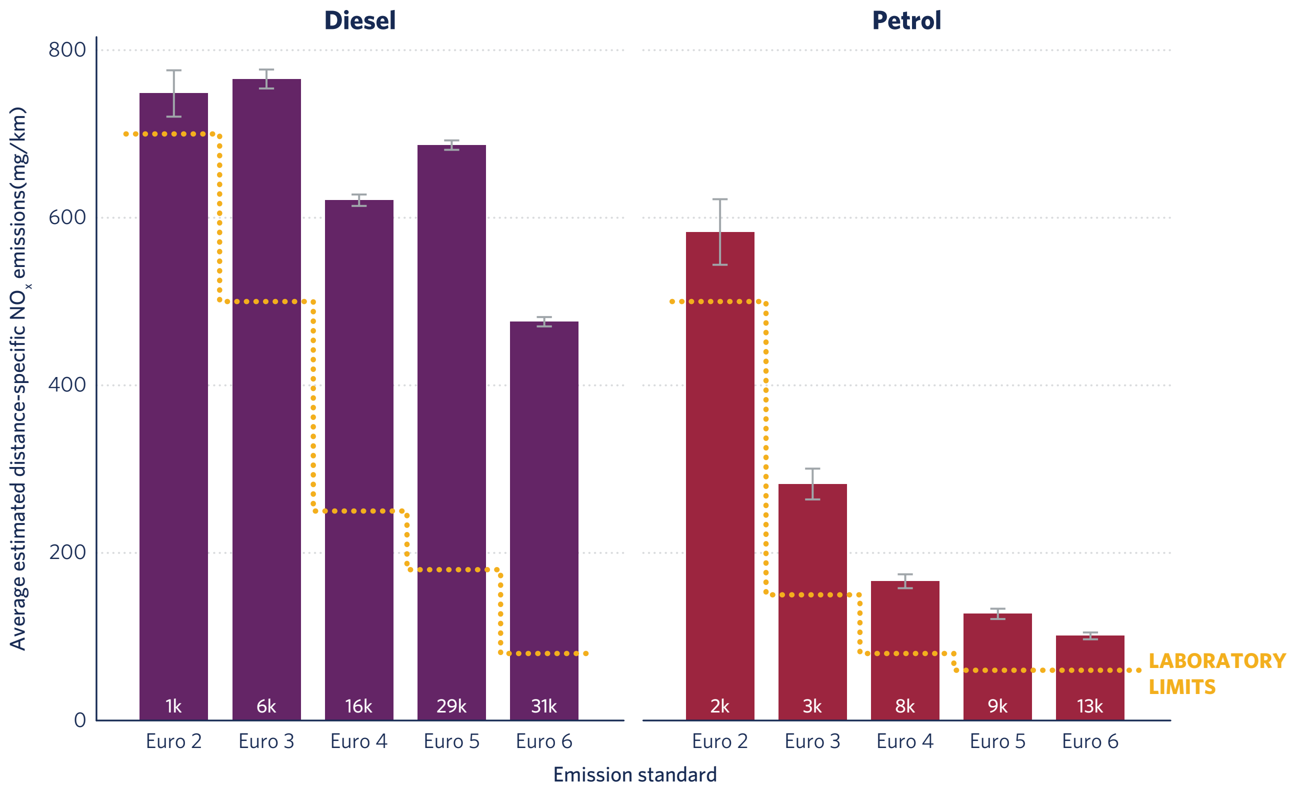

Figure 2. Estimated average distance-specific NO_x emissions by fuel type and Euro standard for passenger cars measured in Paris in summer 2018. The number of measurements is presented at the bottom of each bar. Whiskers represent the 95% confidence interval of the mean.

to the market. In the absence of sufficient real-world measurements to generate emission factors for Euro 6d-TEMP and Euro 6d vehicles, in this analysis we assume that NO_x emissions of diesel vehicles certified to these standards are equivalent to the regulated on-road not-to-exceed (NTE) limits. For Euro 6d-TEMP vehicles, this is roughly a 65% reduction in NO_x emissions compared to earlier Euro 6 models calculated from the results of the Paris campaign.[20] This analysis optimistically considers no emission deterioration over the lifetime of these new vehicle models. Deterioration and other potential factors that could lead to elevated NO_x emissions from Euro 6d vehicles are addressed in the discussion section. For RDE-compliant petrol vehicles, we assume real-world NO_x emissions continue to align with the average petrol Euro 6 NO_x emissions measured in other European cities, because these levels are already below the upcoming NTE limit for petrol.[21]

Table 3. Passenger car NO_x emission factors for the hottest months of the year in Paris, by fuel type and Euro standard

	NO_x emission factors for the hottest months of the year in Paris (mg/km)	
	Diesel	**Petrol**
Euro 1	1,346	756
Euro 2	748	585
Euro 3	766	281
Euro 4	621	166
Euro 5	686	127
Euro 6b	476	100
Euro 6d-TEMP	168	72
Euro 6d	114	72

PASSENGER CAR NO_X EMISSION FACTORS FOR THE COLDEST SIX MONTHS OF THE YEAR

NO_x emissions from diesel passenger cars are known to be influenced by ambient temperature, with temperatures below 20°C resulting in elevated emissions, which also occurs with temperatures higher than 30°C. However, this relationship has not

20 Tim Dallmann, Yoann Bernard, Uwe Tietge, and Rachel Muncrief, *Remote Sensing of Motor Vehicle Emissions in Paris* (September 2019), https://theicct.org/publications/on-road-emissions-paris-201909

21 NO_x emissions from petrol Euro 6 vehicles in Paris were higher compared to CONOX cities and likely linked to the lower vehicle speeds. The RDE regulation is expected to improve the robustness of NO_x emissions of petrol vehicles at low speeds setting a NTE in urban conditions.

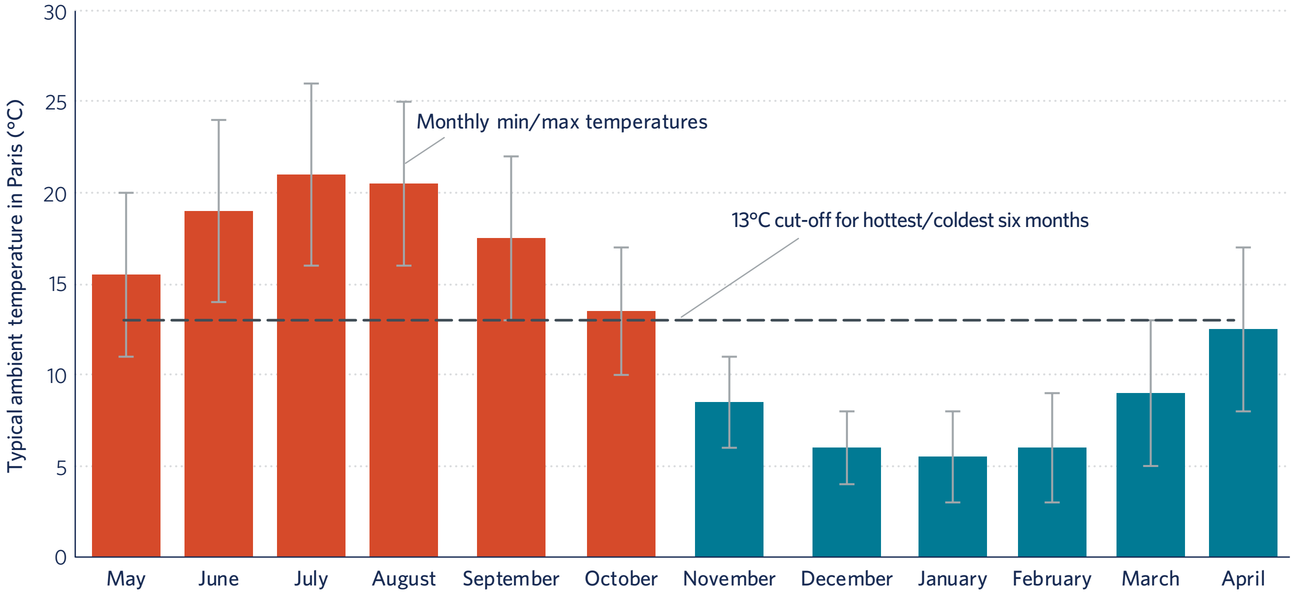

Figure 3. Typical monthly temperatures in Paris. The whiskers represent the typical minimum and maximum temperatures during the day. The bar heights indicate the average of the daily minimum and maximum.

been observed for petrol vehicles.[22] Because the Paris testing campaign occurred in summer, we specifically developed adjustment factors for this analysis to estimate diesel passenger car emissions during the coldest months of the year to better capture the LEZ benefits over the course of a full year.

We derived these adjustment factors using the CONOX 2019 remote-sensing database that includes more than 600,000 light-duty vehicle measurements from Spain, the United Kingdom, France, Sweden, and Switzerland.[23] The Paris data were excluded from the scaling factors calculation.

Figure 3 shows typical monthly temperatures in Paris over a 30-year period (1981–2010).[24] The six hottest months of the year span from May to October, and the coldest from November to April. Based on these data, a threshold of 13°C was used to differentiate the six hottest months from the six coldest months of measurements in the CONOX database.

Vehicle specific power (VSP), used as a surrogate of the power demand necessary to move the vehicle, is another parameter known to influence NO_x emissions from diesel passenger cars.[25] It can be estimated from remote-sensing records using vehicle speed, acceleration, and road grade. The average VSP measured in Paris was lower than the average VSP in the CONOX dataset. Therefore, we filtered the CONOX dataset using VSP bounds to reflect average VSP conditions comparable to those measured in Paris. These were 0 kW/t for the lower bound and 10 kW/t for the upper bound.

22 Tim Dallmann, Yoann Bernard, Uwe Tietge, and Rachel Muncrief, *Remote Sensing of Motor Vehicle Emissions in Paris* (September 2019), https://theicct.org/publications/on-road-emissions-paris-201909 Stuart K. Grange, Naomi J. Farren, Adam R. Vaughan, Rebecca A. Rose, and David C. Carslaw, "Strong Temperature Dependence for Light-Duty Diesel Vehicle NO_x Emissions," *Environmental Science & Technology* (16 May 2019), https://pubs.acs.org/doi/10.1021/acs.est.9b01024

23 Jens Borken-Kleefeld, Stefan Hausberger, Peter McClintock, James Tate, David Carslaw, Yoann Bernard, and Åke Sjödin, *Comparing Emission Rates Derived from Remote Sensing with PEMS and Chassis Dynamometer Tests—CONOX Task 1 Report*, Federal Office for the Environment, Switzerland (May 2018), https://www.ivl.se/download/18.2aa26978160972788071cd7b/1529408235244/comparing-emission-rates-derived-from-remote-sensing-with-pems-and-chassis-dynamometer-tests-conox-task1-report.pdf

24 National Centers for Environmental Information, *National Centers for Environmental Information* (2019), https://www.ncdc.noaa.gov/

25 Yoann Bernard, Uwe Tietge, John German, and Rachel Muncrief, *Determination of Real-World Emissions from Passenger Vehicles Using Remote Sensing Data* (June 2018), https://theicct.org/publications/real-world-emissions-using-remote-sensing-data

Table 4 shows the assumed scaling factors, which for diesel vehicles are derived from the ratio of remote-sensing NO_x measurements between the coldest and hottest six months, that is by averaging CONOX measurements for NO_x respectively below and above 13°C. For petrol, we do not apply any adjustment for ambient temperature, as discussed earlier. We also did not adjust emissions for Euro 6d-TEMP and 6d vehicles, as the RDE regulation's moderate boundaries cover typical winter temperatures in Paris. We did not evaluate the potential for increases in emissions of RDE-certified vehicles during exceptional temperatures. In particular, the extended temperature range of the RDE protocol allows emissions to increase by 60% between -7°C and 0°C, and between 30°C and 35°C. Considering these effects could lead to decreased NO_x benefits for LEZ phases that still allow Euro 6d-TEMP and 6d diesel vehicles, or increased NO_x benefits for LEZ phases that exclude these vehicles.

Table 4. Hottest to coldest months NO_x adjustment factors based on CONOX data, by fuel type and Euro standard

	Hottest to coldest months NOx adjustment factors	
	Diesel	Petrol
Euro 2	1.37	1.00
Euro 3	1.17	1.00
Euro 4	1.28	1.00
Euro 5	1.21	1.00
Euro 6b	1.19	1.00
Euro 6d-TEMP	1.00	1.00
Euro 6d	1.00	1.00

Table 5 shows estimated average NO_x emission factors (mg/km) for diesel and petrol passenger cars in Paris for the coldest 6 months of the year. Emission factors of petrol and all Euro 1 passenger cars were not adjusted for ambient temperature, for reasons previously discussed.

Table 5. Passenger car NO_x emission factors for the coldest months of the year in Paris, by fuel type and Euro standard

	NO_x emission factors for the coldest months of the year in Paris (mg/km)	
	Diesel	Petrol
Euro 1	1,346	756
Euro 2	1027	585
Euro 3	894	281
Euro 4	794	166
Euro 5	833	127
Euro 6	565	100
Euro 6d-TEMP	168	72
Euro 6d	114	72

CURRENT SHARE OF PASSENGER CAR ACTIVITY BY FUEL TYPE AND EURO STANDARD

To characterize the current share of Paris' passenger car activity by fuel and Euro standard, we derived age distributions for diesel and petrol passenger cars using data from traffic counts conducted in 2014 and 2016 and from the 2018 remote sensing campaign (see Figure 4).[26] Vehicle counts were used as a proxy for the share of vehicle activity by fuel type and vehicle age.

We approximated the corresponding Euro standard for each vehicle age by associating its registration date with the most recently implemented emission standard (see Table 6). Because of the uncertainty with respect to when in the year a vehicle was registered and whether or not the vehicle was type-approved to the next standard, we considered two cases. In the optimistic case, we assumed vehicles were registered at the end of the year and certified to the newest standard possible, corresponding to type approval dates in Table 6. In the pessimistic case, we assumed vehicles were registered at the beginning of the year and had the oldest standard possible, corresponding to the all vehicle sales and registration dates in Table 6. For example, passenger cars registered in 2014 are assumed to comply with Euro 5b in the pessimistic scenario and Euro 6 in the optimistic scenario.

26 Source of traffic counts: Ville de Paris, Enquête plaques, novembre 2014 et novembre 2016. Source of the remote-sensing data: Tim Dallmann, Yoann Bernard, Uwe Tietge, and Rachel Muncrief, *Remote Sensing of Motor Vehicle Emissions in Paris* (September 2019), https://theicct.org/publications/on-road-emissions-paris-201909.

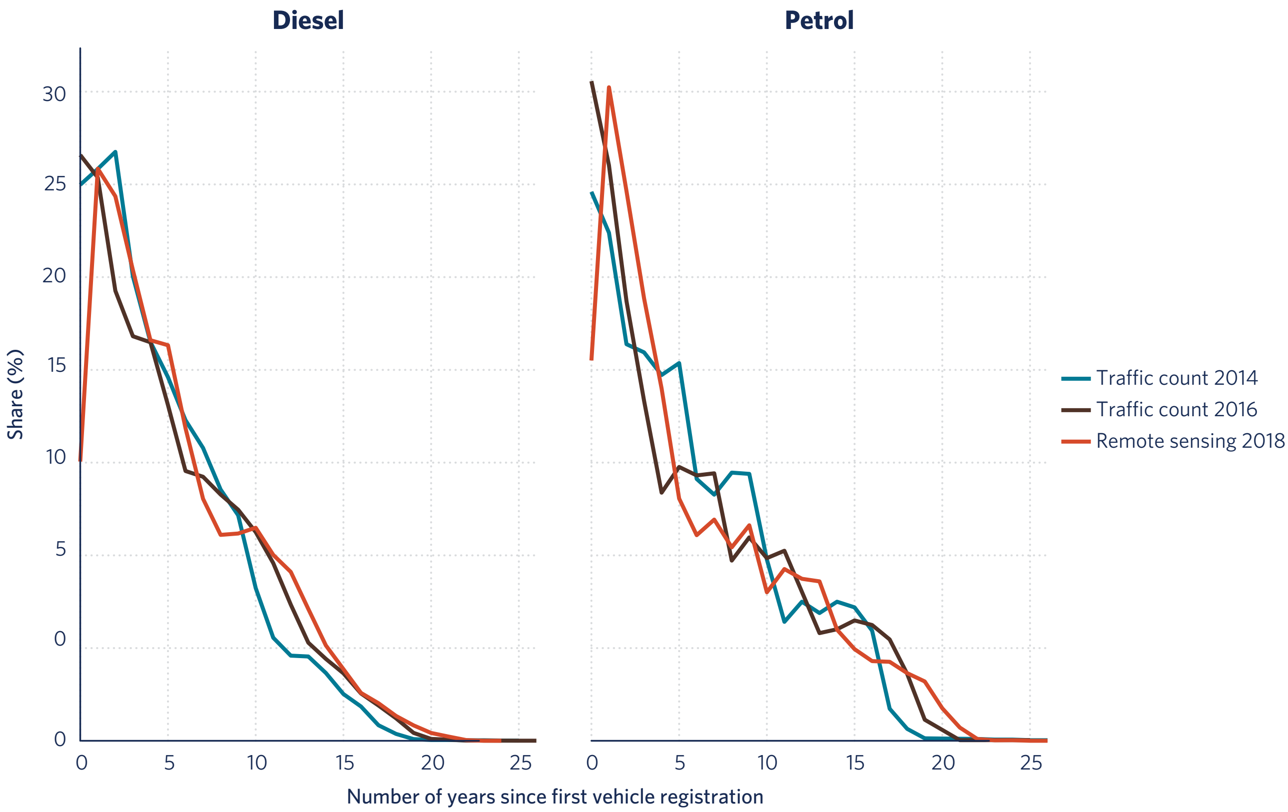

Figure 4. Share of traffic counts and remote sensing measurements by number of years since first vehicle registration.

Table 6. Implementation timeline of EU passenger car emission standards.

Standard	New vehicle type approvals	All vehicle sales and registrations
Euro 1	Jul-92	Jan-93
Euro 2	Jan-96	Jan-97
Euro 3	Jan-00	Jan-01
Euro 4	Jan-05	Jan-06
Euro 5a	Sep-09	Jan-11
Euro 5b	Sep-11	Jan-13
Euro 6b	Sep-14	Sep-15
Euro 6d-TEMP	Sep-17	Sep-19
Euro 6d	Jan-20	Jan-21

TURNOVER CALCULATIONS FOR PROJECTED PASSENGER CAR ACTIVITY SHARES

The effects of natural fleet turnover were simulated by assuming constant age distributions for diesel and petrol passenger cars. This assumption was informed by the relatively stable age distributions observed in Paris from 2014 to 2018. Hence, for each year of the analysis, we applied the same age distributions to calculate the share of diesel and petrol passenger cars by registration year. The methods for estimating the fleet share by Euro standard were the same as previously described. For this analysis, we assumed no change in the shares of new registrations of diesel versus petrol passenger cars before accounting for the impacts of the LEZ. Using the shares of vehicle measurements from the remote sensing campaign, we assumed petrol vehicles accounted for 30.5% of passenger car activity and diesel vehicles accounted for the other 69.5%. Although these assumptions are based on data collected at only three locations in Paris in summer 2018, they are comparable to an earlier estimate from Airparif that diesel represented 65% of total kilometers driven by passenger cars.[27] With these estimates for the share of passenger car activity by fuel type and Euro standard, we then applied the previously discussed NO_x emission factors to calculate the passenger car fleet average NO_x emission factor.

27 Airparif, *Étude prospective dans le cadre de la création d'une zone a circulation restreinte à Paris* [in French] (October 2016), https://api-site.paris.fr/images/87626

EFFECTS OF THE PARIS LEZ THROUGH 2024

To evaluate the effects of the Paris LEZ on passenger car fleet average NO_x emission factors, we use several scenarios based on the draft implementation schedule for the City of Paris (see Table 2). Our analysis covers the first five phases, corresponding to the years 2016, 2017, 2019, 2022, and 2024. For each phase, we estimate the fleet average NO_x emission factor of passenger cars in Paris both with and without the LEZ in effect.

Each successive phase of the LEZ tightens the minimum CRIT'Air certificate requirement for vehicles allowed into the zone based on their fuel type and Euro standard. For this analysis, we conservatively assume that the total level of vehicle activity is not affected by the LEZ and that drivers switch to vehicles that comply with the LEZ requirements. To account for variation in how drivers would choose their replacement vehicles, we evaluate two cases:

- In the worst case scenario, we shift the activity of noncompliant vehicles to vehicles that meet the bare minimum requirements of the LEZ. We assume total activity remains constant for vehicles of the same fuel type if possible. For example, the activity of noncompliant diesel vehicles shifts to newer diesel vehicles. For Phase 5, which requires a CRIT'Air 1 certificate which is unobtainable by diesel passenger cars, we assume diesel vehicle activity shifts to Euro 5 certified petrol vehicles.
- In the best case scenario, we shift noncompliant activity to brand new petrol vehicles, modeling the case where consumers purchase new vehicles in anticipation of the tightening requirements. Plug-in electric and hydrogen fuel cell vehicles are not considered in this analysis (see Discussion).

We calculate baseline activity shares without the LEZ by fuel type and Euro standard for each of the five analysis years under the assumptions of slightly newer vehicles (optimistic scenario) and slightly older vehicles (pessimistic scenario). We evaluate the effects of the LEZ for each of these cases, for both best case and worst case vehicle-switching behavior. From these estimates, we calculate the passenger car fleet average NO_x emission factor for each scenario using the corresponding seasonal emission factors. The subsequent section evaluates the potential effects of alternate LEZ requirements.

ESTIMATED PARIS LEZ EFFECTS ON PASSENGER CAR ACTIVITY SHARES THROUGH 2024

Figure 5 shows the estimated effects of the LEZ on passenger car activity by fuel type and CRIT'Air class from its inception in 2016 through Phase 5 in 2024. In the early stages, the LEZ restricts only petrol and diesel Euro 1 and older vehicles, which account for only a small fraction of passenger car activity. With the introduction of Phase 3 in 2019, the LEZ could begin to have a more noticeable effect on the distribution of vehicles within the LEZ. Because diesel cars certified to Euro 3 no longer meet the LEZ's CRIT'Air requirement, that share of activity is expected to shift to newer vehicles. At this step, this analysis assumes Euro 3 diesels would be replaced either by Euro 4 diesels in the worst case or Euro 6 petrol vehicles in the best case. In Phase 4, the difference of the cleanest share of vehicles activity between the two scenarios is at its highest when consumers can choose between Euro 5 diesels and Euro 6 petrol vehicles to comply with the LEZ requirements. It is only by Phase 5 in 2024, when diesel cars of any Euro standard would no longer meet the minimum requirement for entering the LEZ, that a large share of activity is expected to shift to cleaner vehicles, regardless of how drivers respond.

ESTIMATED PARIS LEZ EFFECTS ON AVERAGE NO_X EMISSION FACTORS THROUGH 2024

Figure 6 shows the projected passenger car average NO_x emission factors for the best case and worst case responses to the LEZ, compared with a baseline scenario without the LEZ. The results shown use summer emission factors and optimistic registration assumptions. Results for all combinations of seasonality and registration assumptions are in shown Figure 7. Perhaps surprisingly, the first few phases of the LEZ may have little to no effect on the average NO_x emission factor of passenger cars, depending on how drivers comply with the LEZ. The main driver of this effect is that Euro 5 diesels are classified as CRIT'Air 2, which are expected to be allowed for the first four phases of the LEZ (until Phase 5 in 2024). However, the annual average NO_x emission factor of Euro 5 diesels is only about 15% lower than Euro 2 diesels, 7.5% lower than Euro 3 diesels, and slightly above that of Euro 4 diesels. Hence, as long as Euro 5 diesels are eligible to enter the LEZ, the NO_x benefits depend on drivers choosing to

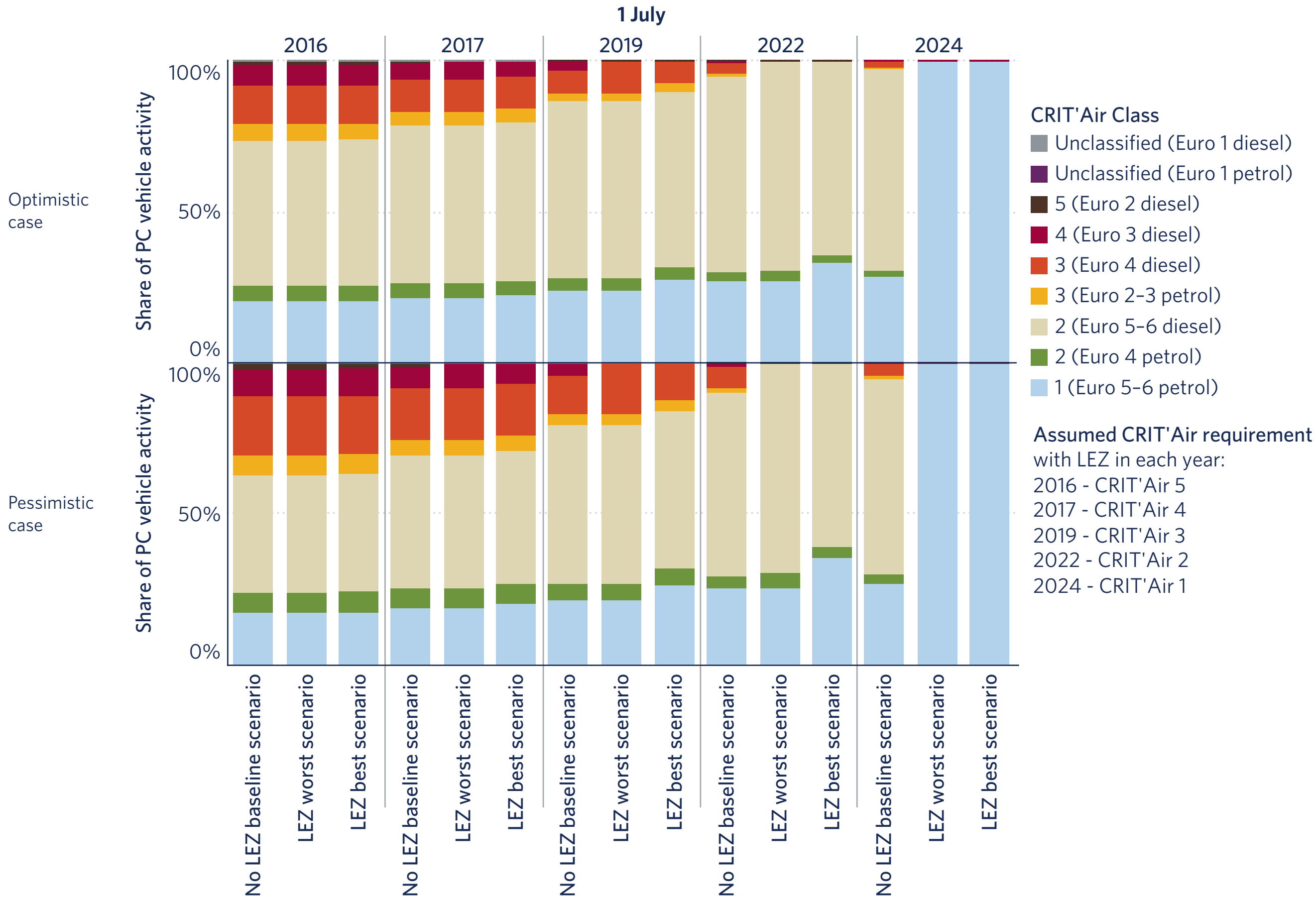

Figure 5. Estimated effects of Paris LEZ on passenger car activity by fuel type and CRIT'Air class.

switch to cleaner vehicles rather than meeting the bare minimum requirements for access.

In contrast to Phases 1 through 4, Phase 5 is estimated to yield substantial NO_x benefits regardless of how drivers choose to comply with the LEZ. This effect is produced by the projected shift from diesels to petrol passenger cars meeting at least Euro 5 standards. As previously noted, Euro 6 petrol passenger cars emit about one-seventh the average NO_x of Euro 5 diesels and one-fifth that of the average Euro 6 diesel. Under a baseline scenario without the LEZ, average passenger car NO_x emission factors in 2024 are projected to be 47% to 62% below 2016 levels, depending on the season and registration assumptions (see Figure 7). With the implementation of Phase 5 of the LEZ in 2024, passenger car NO_x emission factors are projected to be 76% to 87% below 2016 levels. Achieving a similar level of emission reduction without the LEZ and without rapid electrification would take another 7 to 10 years. The policy implications of these findings are considered in the Discussion section.

EFFECTS OF ALTERNATE LEZ RESTRICTIONS

The analysis in the preceding section is based on the assumption that the LEZ implementation schedule will occur as drafted. In this section, we explore the potential effects of two hypothetical changes to this schedule.

EARLIER IMPLEMENTATION OF PHASE 5

Phase 5 is currently scheduled to go into effect in time for the 2024 Summer Olympics in Paris, during which the mayor has committed to attain European air quality limits.[28] As evaluated in the previous section, the restriction on diesel passenger cars during Phase 5 would substantially reduce average passenger car NO_x emission factors in 2024. Earlier implementation of Phase 5 is one potential policy option to achieve these air quality and health benefits sooner. We find that compared with the draft implementation schedule,

28 La Ville de Paris, La Zone à faibles émissions (ZFE) pour lutter contre la pollution de l'air [in French] (17 September 2019), https://www.paris.fr/pages/nouvelle-etape-crit-air-des-le-1er-juillet-2017-4834

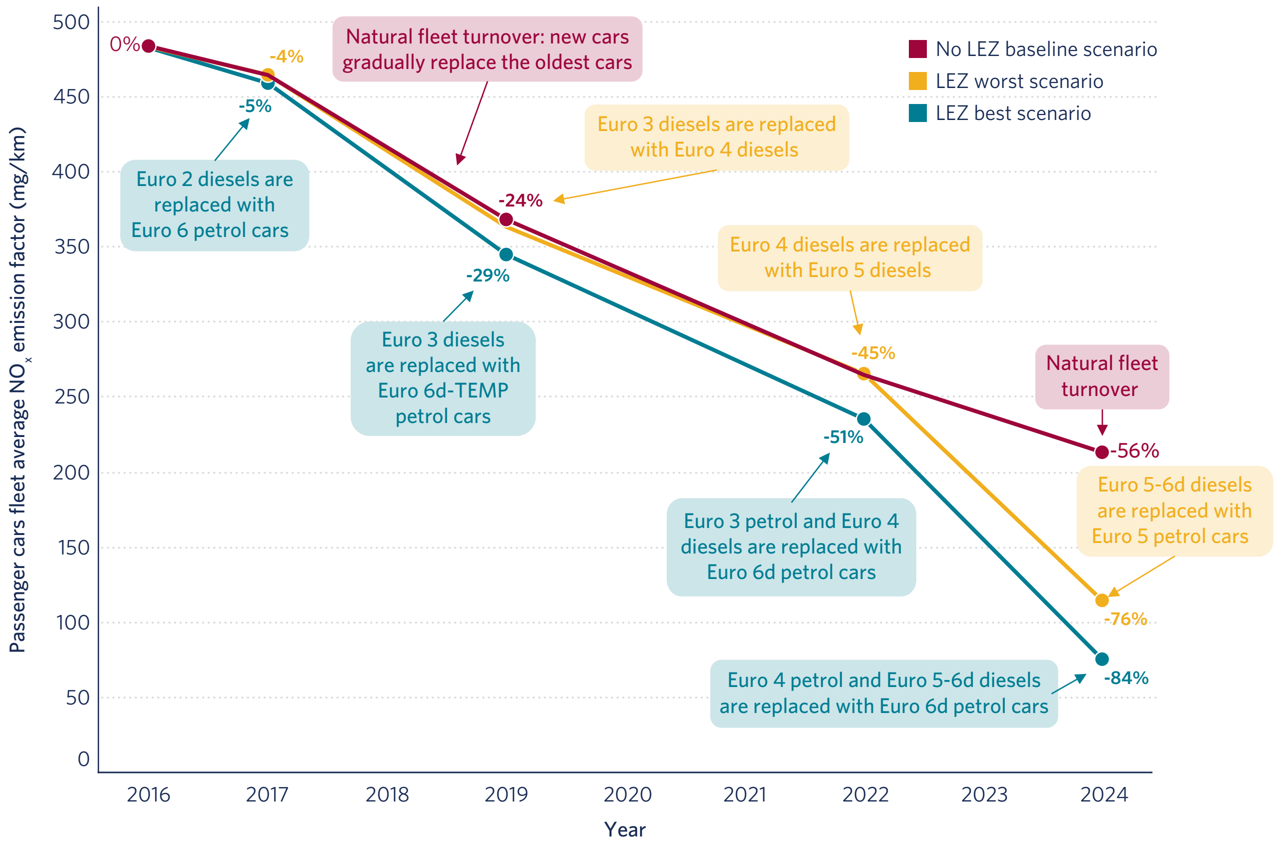

Figure 6. Estimated effects of Paris LEZ on passenger car fleet average NO_x emission factors, with summer emission factors and optimistic registration assumptions.

which will require CRIT'Air 3 in 2020 and CRIT'Air 2 in 2022, the benefits of early implementation of Phase 5 are significant: Accelerating the implementation of Phase 5 to 2020 would yield a 72% to 77% total reduction in passenger car NO_x emissions, whereas a 2022 implementation would yield a 66% to 71% reduction (see Figure 8).

REPLACEMENT OF NONCOMPLIANT VEHICLES WITH ZERO-EMISSION VEHICLES

The effectiveness of the LEZ depends on how drivers respond when their vehicles do not meet the requirements of the zone. In the preceding analyses, we conservatively assume that drivers would not change their travel behavior but instead would buy a new or used car that meets the zone's minimum requirement. The effect of the LEZ is significantly greater if restricted vehicle activity is allocated to zero-emission vehicles, which would result in up to a 91% reduction in NO_x emissions compared to without the LEZ (see Figure 9). This low level of pollution could also be obtained if drivers respond by switching to other zero-emission modes such as walking, biking, or the Paris Métro.

DISCUSSION

Our findings indicate that under the draft implementation schedule for the Paris LEZ, a substantial shift to cleaner passenger cars and attendant NO_x reductions can be expected from 2024 onward. This section discusses how various policy decisions could accelerate, augment, or diminish these benefits. For that, we discuss the policy implications for Paris and other cities and provide recommendations for future research.

POLICY IMPLICATIONS FOR PARIS

The analysis presented above suggests the following recommendations to the Paris LEZ to further reduce NO_x emissions from passenger cars.

- **Tighten access regulations for the LEZ at a faster pace.** Our analysis shows that achieving substantial NO_x benefits for passenger cars regardless of how drivers choose to comply with the LEZ is only expected from 2024 (Phase 5) onward. Given

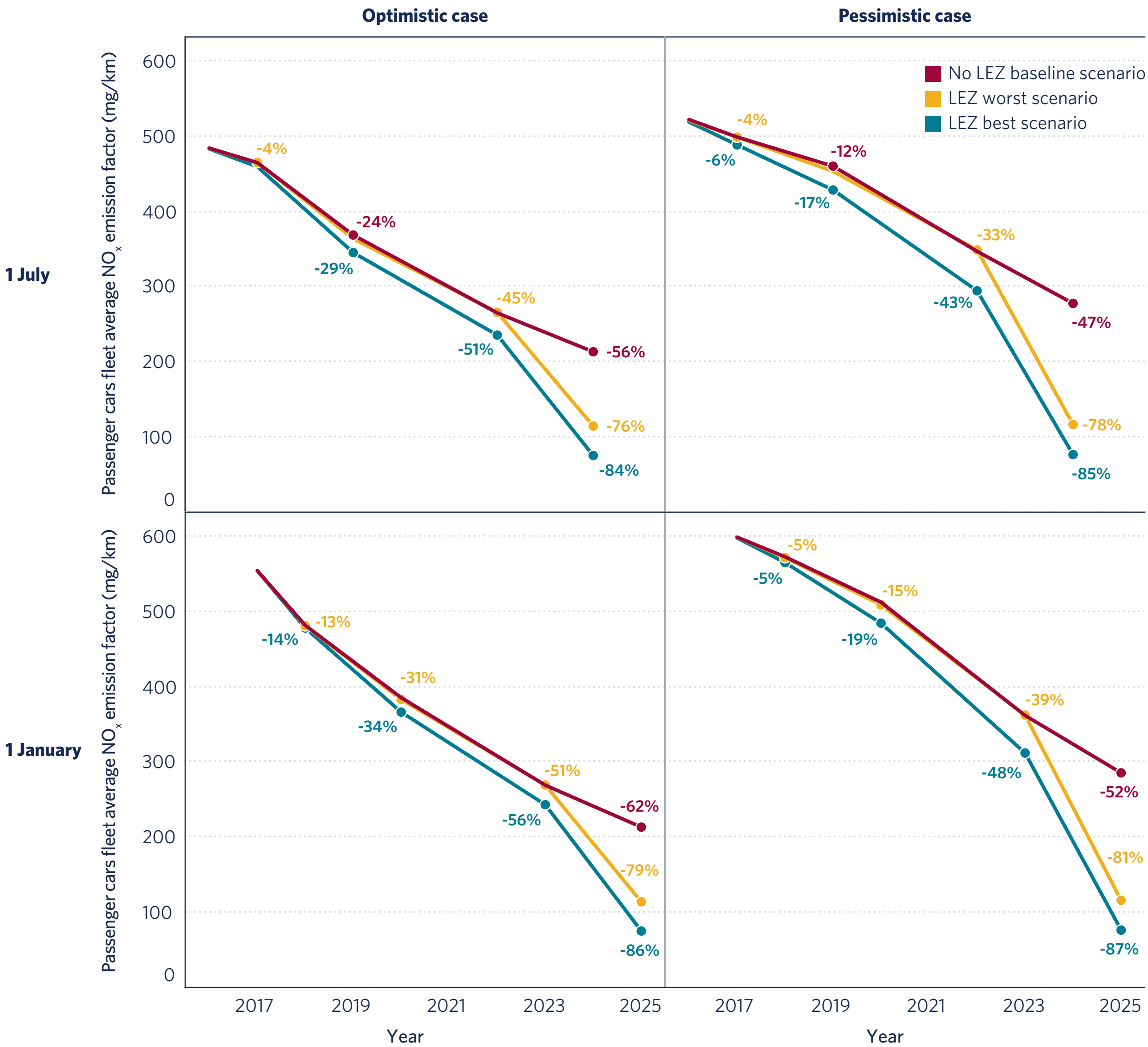

Figure 7. Estimated effects of Paris LEZ on passenger car fleet average NO_x emission factors, including the effects of seasonality (summer and winter emission factors), consumer responses to the LEZ (worst and best cases), and uncertainty in registration/type-approval data (pessimistic and optimistic registration cases).

the substantial NO_x reductions expected at this phase, introducing this phase before 2024 could be worthwhile. Compared with the current schedule, moving Phase 5 two years earlier to 2022 would reduce NO_x emissions in that year by two-thirds.

This analysis did not model the effects of Phase 6 in 2030, when only vehicles with a green CRIT'Air certificate would be allowed in the zone. Considering the magnitude of that transition, formalizing the timeline soon would provide an important signal for current vehicle purchase decisions, because vehicles purchased today are likely to have a lifetime that extends past 2030. The enforceability of Phase 6 and the benefits of earlier LEZ phases both could be enhanced by continuing to develop complementary policies for fleet electrification and mode shift.

- **Incentivize replacement with zero-emission vehicles.** The emission reductions resulting from the LEZ will be augmented if restricted vehicles are replaced with zero-emission vehicles. However, the upfront costs of zero-emission vehicles are a known barrier to their uptake, particularly for drivers with low to moderate incomes who are more likely to own older vehicles. In 2020, the French government

Figure 8. Estimated passenger car fleet average NO_x emission factor in 2020 and 2022 without the LEZ, with the proposed LEZ, and with earlier implementation of Phase 5.

provides a maximum €6,000 one-time bonus for the purchase of a new car or van with an emissions rating at or below 20 g CO_2/km. In addition, the government offers a conversion bonus for scrapping an older car in favor of a less-polluting new or used car. The amount is up to €5,000 for buying a battery electric vehicle or plug-in hybrid, and up to €4,000 for CRIT'Air 1 or 2 petrol or diesel car. Citizens living in the City of Paris or the Greater Paris region also benefit from a local conversion bonus up to €6,000 for the purchase of a new or used electric, hydrogen, hybrid or compressed natural gas vehicle.[29] In Paris, additional financial support helps individuals give up their older cars and encourages them to switch to an e-bicycle or e-moped, or to the public bicycle sharing program Vélib'.[30] The existence of these substantial vehicle replacement incentives suggests that the LEZ requirements could be tightened at an accelerated schedule without unduly penalizing current owners of older vehicles. Because vehicles purchased today are likely to last more than a decade, adjusting these incentives to heavily favor replacement with green CRIT'Air vehicles today would increase the enforceability of Phase 6 in 2030.

- **Automate enforcement of the LEZ.** The expected emission benefits of the LEZ will not materialize unless vehicles comply with the LEZ requirements. As of March 2020, enforcement of the LEZ in Paris was limited to police visual inspections. Although this method may be suitable while the LEZ affects only a small share of vehicles, it is unlikely to be able to keep up with the implementation of Phase 5, which could affect a large portion of the vehicle fleet. Other cities such as London and Brussels have developed systematic enforcement programs that use a network of cameras with automated license plate recognition. A similar approach can be considered for Paris, particularly in preparation for Phase 5. The French Loi d'orientation des mobilités, or Mobility Guidance Law, of 24 December 2019 recently facilitated the automated recording of vehicles not complying with the LEZ.[31]

29 Metropole du Grand Paris, *Metropolis rolls clean!* [in French] (2019), https://www.metropolegrandparis.fr/fr/metropole-roule-propre-179

30 La Ville de Paris, *Les aides financières pour inciter à des mobilités propres* [in French] (28 October 2019), https://www.paris.fr/pages/lutte-contre-la-pollution-les-aides-a-la-mobilite-5373

31 République Française, Loi number 2019-1428 du 24 décembre 2019 d'orientation des mobilités [in French] (24 December 2019), https://www.legifrance.gouv.fr/eli/loi/2019/12/24/TRET1821032L/jo/texte

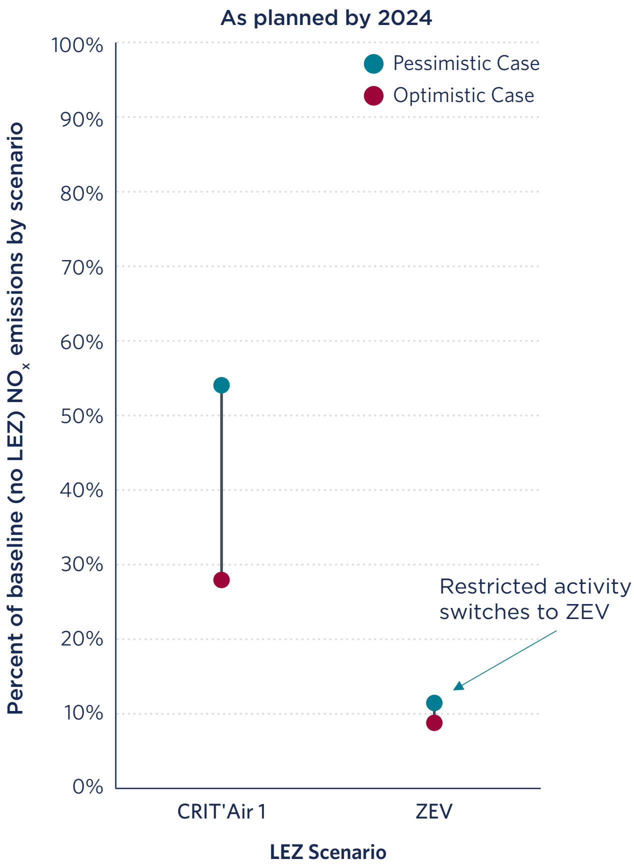

Figure 9. Percent of baseline (no LEZ in effect) passenger car NO_x emissions in 2024 by scenario: Phase 5 as planned (current CRIT'Air 1) and Phase 5 assuming restricted activity switches to zero-emission vehicles (ZEV).

POLICY IMPLICATIONS FOR OTHER CITIES

This analysis of the potential effects of the LEZ in Paris can also provide insights for other cities that are implementing or modifying their access regulations.

- National labeling programs such as CRIT'Air can be helpful for allowing cities to develop and enforce LEZs and adjust the timing and stringency according to local conditions.
- Labeling programs, access restrictions, and purchase incentives should be based on real-world emissions performance in order to guarantee their effectiveness. For example, the negligible real-world NO_x improvements from Euro 2 to Euro 5 for diesel passenger cars cast some doubt as to whether Euro 5 diesels belong in CRIT'Air 2 or should rather be reclassified as CRIT'Air 3.[32] For comparison, the London Ultra Low Emission Zone in place since April 2019 imposes an access fee for diesel Euro 5 and older passenger cars.
- As long as pre-Euro 6 diesels are eligible to enter the LEZ, the NO_x benefits will depend on drivers choosing to switch to cleaner vehicles rather than meeting the bare minimum requirements. Cities should schedule access restrictions for pre-Euro 6 diesels as early as possible.
- Establishing a clear timeline is important to signal consumers to shift their purchase decisions. However, there is a trade-off between lead time and benefits, given that the purpose of the LEZ is to accelerate fleets' transitions to cleaner vehicles. Supporting incentives to scrap older vehicles and shift new purchases to zero-emission vehicles could reduce the amount of lead time needed to implement more advanced LEZ stages.

RECOMMENDATIONS FOR FURTHER RESEARCH

This analysis of the LEZ in Paris examines the potential effects on passenger car NO_x emissions performance. Further analysis could address the following topics.

- The LEZ applies to all on-road vehicle types such as light-commercial, buses, or trucks and is expected to limit access to most polluting vehicles for NO_x, but also for other regulated pollutants such as primary particulate matter, carbon monoxide, and hydrocarbon emissions. Further research should evaluate the effects for other pollutants and vehicle types.
- The analysis does not evaluate the potential effects of the LEZ on reducing overall passenger car activity. Further studies that monitor vehicle traffic, public transit ridership, and walking and cycling activity, and evaluate the effects on overall passenger car activity could be informative for other cities considering LEZs.
- The diesel share of new passenger car registrations has been declining in France in recent years.[33] The

32 The differences are more tangible for tailpipe $PM_{2.5}$ because all Euro 5b diesels are equipped with diesel particulate filters.

33 Uwe Tietge, "2017 Year in Review: European Diesel Down, Electric Vehicles on the Rise," The International Council on Clean Transportation (blog), January 24, 2018, https://www.theicct.org/blog/staff/2017-year-review-european-diesel-down-electric-vehicles-rise

baseline scenario in this analysis uses the latest available data for the fleet in Paris measured in summer 2018 and does not assume further declines in the market share of new diesel cars. If the trend of declining diesel market share were to continue for the next several years, at the current rate of fleet renewal, Paris's fleet share of diesel power trains could drop to below 50% in the 2022–2024 time frame. To facilitate accurate monitoring and evaluation of the LEZ, information on the share of vehicle activity in Paris by power train and emission standards could be regularly updated based on future traffic count campaigns.

- Air quality monitoring data could be used to track the effectiveness of the LEZ and other policies in reducing traffic-related ambient pollutant concentrations. These data could be combined with continued remote sensing campaigns or permanent installations to facilitate ex post evaluations of recent policy actions and inform future planning efforts.
- The LEZ in Paris operates only during the daytime and covers only a certain area of the city. The current LEZ in the Greater Paris region is less stringent but covers a larger area. Our analysis does not evaluate the effects of an extended operating time—24 hours per day, every day of the week, year-round—nor does it evaluate the effects of different geographical coverages. These factors could be considered in future research, particularly where policymakers are delineating a new LEZ or considering expansion of an existing LEZ.
- The emission factors of RDE-compliant vehicles applied in this analysis were based on early findings and regulatory on-road limits; however, diesel NO_x emissions outside the scope of the RDE test procedure may be substantially higher.[34] Further, the emissions durability of these new diesel models is unknown: Because the current regulatory requirement for in-service conformity is limited to 5 years or 100,000 km—whichever comes first—there is significant potential for further deterioration over the normal life of vehicles after the window for in-service conformity.[35] The emission factors applied in this analysis can therefore be considered optimistic. Upcoming emission monitoring using remote sensing will enable updates to these emission factors.

34 Ricardo Suarez-Bertoa, Victor Valverde, Michael Clairotte, Jelica Pavlovic, Barouch Giechaskiel, Vicente Franco, Zlatko Kregar, and Covadonga Astorga, "On-Road Emissions of Passenger Cars beyond the Boundary Conditions of the Real-Driving Emissions Test," *Environmental Research* 176 (September 2019), https://www.sciencedirect.com/science/article/pii/S001393511930369X

35 Felipe Rodríguez, Yoann Bernard, Jan Dornoff, and Peter Mock, *Recommendations for Post-Euro 6 Standards for Light-Duty Vehicles in the European Union* (October 2019), https://theicct.org/publications/recommendations-post-euro-6-eu

TO FIND OUT MORE

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

The Real Urban Emissions Initiative (TRUE) is a partnership of the FIA Foundation, the International Council on Clean Transportation, Global NCAP, Transport and Environment, and C40 Cities.

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