THE REAL URBAN EMISSIONS INITIATIVE

Life-cycle greenhouse gas impact of the low-emission zone in Brussels

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

EXECUTIVE SUMMARY

Motor vehicles contribute significantly to air pollution in the Brussels Capital Region (BCR) and present significant health risks for residents. In 2021, The Real Urban Emissions (TRUE) Initiative published a report on the state of real-world vehicle emissions in the BCR, demonstrating the potential benefits of the Brussels Low Emission Zone (LEZ) for reducing pollutant emissions. TRUE now extends this research and assesses the role of the LEZ and of Good Move policies—modal shift and traffic reduction strategies under the BCR's 2020–2030 mobility plan—in shaping the trajectory of the region's greenhouse gas (GHG) emissions. This study evaluates how these policies contribute to the BCR's ambitious GHG reduction goals under the European Union's Effort Sharing Regulation.

This study integrates previous emissions modeling of the Brussels vehicle fleet performed by Brussels Environment with extensive literature on life-cycle GHG emissions in Belgium and Europe. We estimate annual and cumulative life-cycle GHG emissions under three scenarios:

- **Business as Usual (BAU)**, with a base year of 2019, prior to LEZ implementation;
- **LEZ**, according to the original LEZ schedule in place before October 2024; and
- **LEZ + Good Move**, again assuming the original LEZ schedule.

The addition of the LEZ + Good Move policy scenario—which accounts for measures such as zones with limited access and one-way traffic—allows us to examine the impacts of reducing vehicle activity in addition to changing the composition of the vehicle fleet. Additionally, this analysis includes estimates of further GHG reductions under additional policy scenarios, such as taxing large-segment passenger cars and restricting the lightest-segment internal combustion engine heavy-duty vehicles.

The bulk of this analysis was conducted prior to the October 4, 2024, vote by the Brussels Parliament delaying the 2025 LEZ implementation step to 2027, and therefore is based on the original LEZ schedule. However, we additionally model the impact of this confirmed delay along with a scenario depicting a hypothetical delay of all future LEZ steps. Finally, a sensitivity analysis is conducted using fuel consumption data derived from the 2020 TRUE remote sensing campaign to evaluate GHG reductions under different vehicle operating assumptions.

Key findings and recommendations from our analysis are:

- **The BCR's regional Effort Sharing Regulation goal of a 47% reduction in all-sector GHG emissions by 2030 compared with 2005 is on track under both LEZ scenarios, with the LEZ + Good Move scenario achieving more substantial reductions.** By 2030, annual GHG emission reductions in the LEZ and the LEZ + Good Move scenarios are projected to reach 45% and 54%, respectively, below 2019 levels, largely driven by the ban on most diesel light-duty vehicles and gasoline L-category vehicles (Figure ES1). Considering cumulative emissions, the LEZ scenario avoids 3.9 Mt of GHG emissions (equivalent to the GHG emissions from 83,000 gasoline cars) between 2019 and 2040 compared with the BAU scenario. The LEZ + Good Move scenario avoids 5.7 Mt of GHG emissions (equivalent to the GHG emissions from 121,000 gasoline cars) over this time frame, with Good Move policies accounting for 1.8 Mt of additional savings.

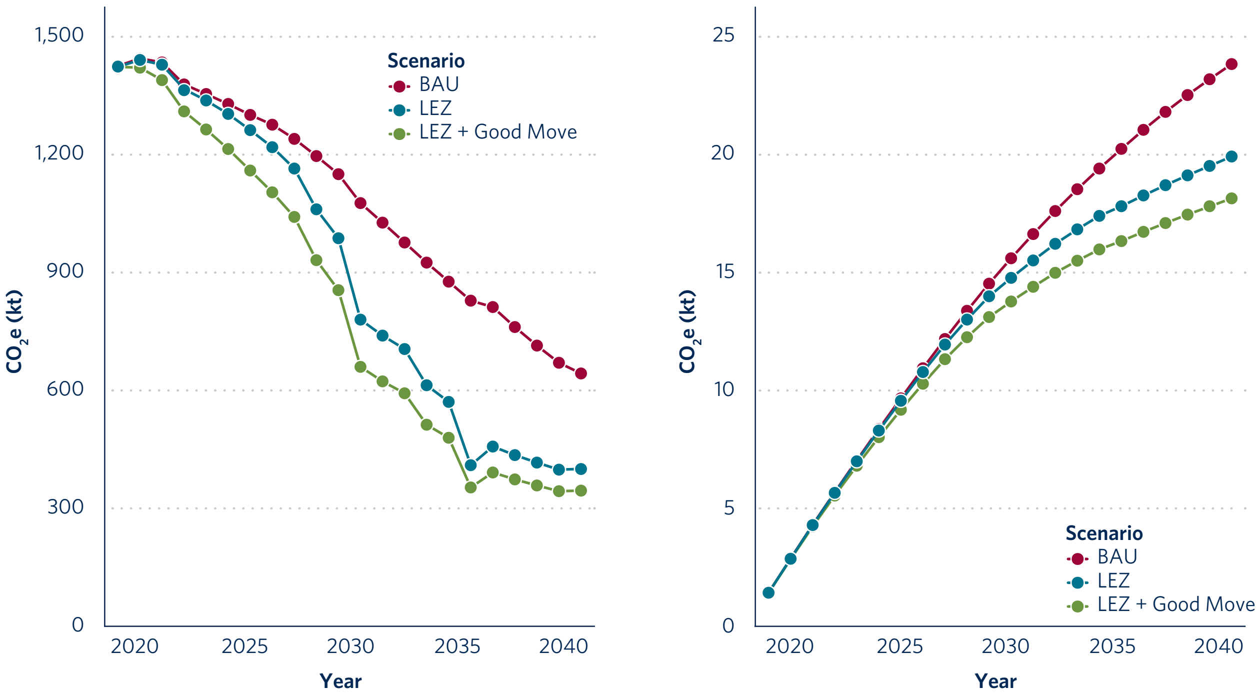

Figure ES1. Annual life-cycle GHG emissions (left) and cumulative life-cycle GHG emissions with a base year of 2019 (right) for each scenario

- **The shift in fleet composition under the LEZ and LEZ + Good Move scenarios highlights the importance of addressing upstream emissions, which are projected to exceed 70% of total emissions by 2040 with the increase in BEV uptake.** This trend emphasizes the increasing importance of vehicle production, battery manufacturing, and electricity sourcing in driving emission reductions as battery electric vehicles comprise a larger share of the fleet under these mobility policies.
- **Additional policy measures to strengthen the LEZ could generate greater GHG emissions saving.** Restricting N2 medium-sized commercial heavy-duty trucks (HDTs), whose growing share of total emissions remain unaddressed by the LEZ, from 2035 results in a 2.4% estimated decrease in annual HDT emissions, equivalent to the GHG emissions from 1,650 gasoline cars in Brussels. Introducing a tax on large-segment vehicles in 2025 to encourage car owners to switch to medium-segment cars would result in cumulative estimated passenger car emissions savings equivalent to the GHG emissions from around 2,300 gasoline cars in Brussels by 2040.
- **Delaying all LEZ measures by 2 years would significantly undermine the benefits of the LEZ on cumulative GHG emissions, as well as on pollutant emissions.** While the approved delay from 2025 to 2027 would likely have a substantial impact on pollutant emissions, such as particulate matter, a 2-year delay on all future LEZ steps would have significant implications for GHG emissions as well. The delay in all future steps is estimated to lower the GHG emission reduction potential by up to 12% compared with the original schedule—3.9% and 11.5% for the LEZ and LEZ + Good Move scenarios, respectively, compared with the original 15.6% and 23.2% by 2040.

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INTRODUCTION

Road transport is one of the primary contributors to air pollution and greenhouse gas (GHG) emissions in the Belgian capital, where over 400 premature deaths were attributed to air pollution in 2023.[1] In 2018, Brussels implemented a low-emission zone (LEZ), a designated area within which high-polluting vehicles are restricted based on vehicle category, fuel type, and emissions standard.[2] Additionally, the LEZ's thermic bans are complemented by Brussels's 2020 regional mobility plan, Good Move, which aims to reduce the motorized transport of people and goods. Circulation plans from Good Move have already demonstrated tangible benefits in the Pentagon area (the city center), such as a 36% increase in bicycling, up to a 25% increase in tram and bus travel speeds, and a 27% decrease in car traffic in just one year.[3] Brussels Environment has emphasized the importance of these dual initiatives, estimating that LEZ and Good Move policies will prevent 100 to 110 premature deaths annually and save up to €350 million in health expenditures each year.[4]

A 2023 Brussels Environment assessment of the early impacts of the LEZ found a 36% reduction in nitrogen oxides (NO_x), 31% reduction in fine particulate matter ($PM_{2.5}$), and 65% reduction in black carbon (BC) emissions from Brussels's fleet after just 5 years of implementation. Nevertheless, in 2023, concentrations of nitrogen dioxide, fine particles, and ozone exceeded the World Health Organization's recommended thresholds by a large margin, although they met European Union (EU) limits for the fourth consecutive year.[5]

Figure 1 depicts the boundaries of the LEZ, comprising a total area of 161 km² across all 19 municipalities in the Brussels Capital Region (BCR), excluding the Brussels Ring and access roads to transit car parks. The LEZ operates on a vehicle restriction schedule based on emission standards, vehicle segments, and fuel types. Following the first planned phaseout in 2027 banning diesel vehicles with two wheels, three upcoming vehicle phaseouts in 2030, 2035, and 2036 are expected to produce significant reductions in pollutant concentrations.[6] By 2030, LEZ restrictions will apply to most light diesel vehicles, and will extend to all light gasoline, compressed natural gas (CNG), and liquefied petroleum gas (LPG) vehicles by 2035.[7] By 2036, the ban will include both diesel and gasoline internal combustion engine city buses, allowing only electric buses. Heavy goods vehicles and coaches are excluded from these phaseouts.[8]

1 Premature deaths are linked to exposure to several pollutants, such that total estimated deaths do not equal the sum of deaths attributed to individual pollutants. Louise Duprez and Simon Dehouck, *Evaluation de La Zone de Basses Émissions – Rapport 2023* [Evaluation of the Low Emission Zone – 2023 Report] (Brussels Environment, 2023), https://lez.brussels/mytax/en/practical?tab=Impact. See also Flemish Environment Agency et al., *Informative Inventory Report* (March 2024), https://www.irceline.be/nl/emissies/IIR2024.pdf.

2 "The Brussels-Capital Region Is a Low Emission Zone," LEZ Brussels, accessed March 14, 2024, https://lez.brussels/mytax/.

3 Aitor Hernández-Morales, "One Year of Good Move in Brussels: Fewer Cars, More Cyclists," POLITICO, September 7, 2023, https://www.politico.eu/article/one-year-good-move-brussels-fewer-cars-more-cyclists/; Denis Balgaranov, "Report: Good Move Plan in Brussels Cuts Public Transport Travel Times by up to a Quarter," TheMayor.EU, March 26, 2024, https://www.themayor.eu/en/a/view/report-good-move-plan-in-brussels-cuts-public-transport-travel-times-by-up-to-a-quarter-11692.

4 "Low Emission Mobility : Rendre l'Air Plus Respirable en Limitant la Circulation des Véhicules Polluants" [Low Emission Mobility: Making the Air More Breathable by Limiting the Circulation of Polluting Vehicles], Brussels Environment, October 23, 2023, https://environnement.brussels/citoyen/nos-actions/plans-et-politiques-regionales/low-emission-mobility-ou-mobilite-basses-emissions-rendre-lair-plus-respirable-en-limitant-la-circulation-des-vehicules-polluants.

5 Duprez and Dehouck, *Evaluation*. The World Health Organization sets annual thresholds for nitrogen dioxide and $PM_{2.5}$ at 10 µg/m³ and 5 µg/m³, respectively, while the EU annual limits are 40 µg/m³ and 25 µg/m³. The World Health Organization's daily maximum for the 8-hour rolling average of ozone concentration is 100 µg/m³, while the EU maximum is 120 µg/m³.

6 At the time this analysis was conducted, the first phaseout step was scheduled for 2025. However, on October 4, 2024, the Parliament of the Brussels-Capital Region voted to push the 2025 step to 2027. The bulk of the analysis is conducted under the assumption that the step is actualized in 2025.

7 Specifically, the 2030 ban includes all diesel passenger cars, diesel small light-commercial vehicles (N1 Class I LCVs), and gasoline mopeds and scooters (L1 and L2). The 2035 ban extends to include all gasoline, compressed natural gas (CNG), and liquefied petroleum gas (LPG) vehicles excluded from the 2030 phase-out, with the addition of Class II and Class III N1 LCVs and motorcycles and scooters (L3-L7). Notably, the Class II and Class III N1 ban includes diesel vehicles and the L3-L7 bans concern gasoline only.

8 "In Practice: Everything You Need to Know about the LEZ in the Brussels-Capital Region," LEZ Brussels, accessed March 27, 2024, https://lez.brussels/mytax/en/practical?tab=Agenda.

Change in average NO_2 concentration (2018–2023)

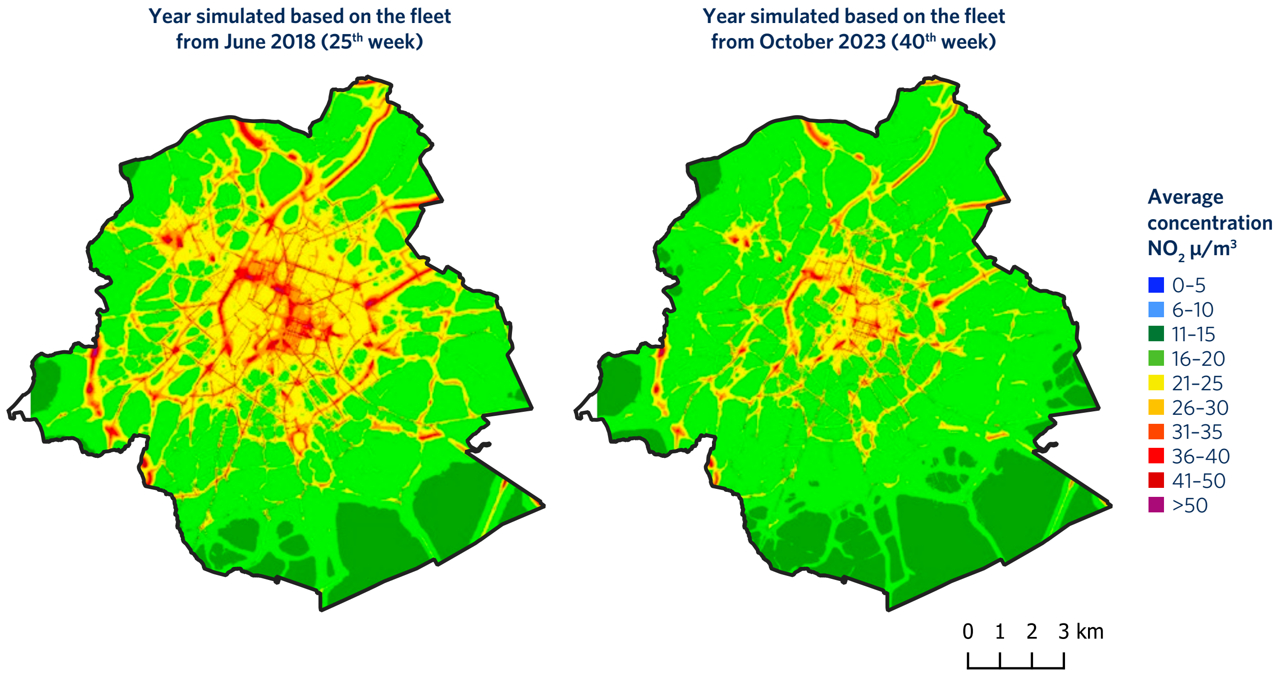

Figure 1. Boundaries of the Brussels LEZ with the spatial distribution of nitrogen dioxide concentrations in 2018 and 2023 (source: Duprez and Dehouck, *Evaluation*.)

Beyond efforts to address pollutant emissions, Brussels is also working to reduce GHG emissions under the European Union's Effort Sharing Regulation, which requires Member States to establish national targets for reducing domestic GHG emissions by 2030.[9] Initially adopted in 2018, the regulation was amended in 2023, when Belgium set a more ambitious goal of reducing all-sector GHG emissions to 47% of 2005 levels by 2030.[10] However, between 2005 and 2023, the transportation sector realized modest reductions of only 8%.[11] The initial success of the LEZ was marked by lower air pollutant concentrations. Still, a comprehensive study is needed to evaluate its impact not only on exhaust GHG emissions, which are directly relevant to the Effort Sharing Regulation's GHG emissions goals, but also on complete life-cycle emissions over time in the BCR. This analysis is particularly relevant for the BCR, which (along with the region of Wallonia) has set a regional GHG reduction target in line with the national goals of 47%.

In this study, we model the GHG emissions from on-road transportation in the BCR under two scenarios that reflect measures impacting the region's fleet composition and mobility over time. (This analysis was conducted prior to the postponement of the phaseout of Euro 5 diesel vehicles and Euro 2 gasoline vehicles from 2025 to 2027, and thus assumes that the phaseout is actualized in 2025 as originally scheduled.) The LEZ scenario captures the implementation of the LEZ and models the changes in vehicle composition as restrictions on internal combustion engine vehicles (ICEVs) are phased in. The LEZ + Good Move scenario considers the LEZ policy alongside modal shift and traffic reduction strategies under the Good Move mobility plan, which include zones with limited access and adjustments to driving directions.[12] Effectively, the LEZ + Good Move scenario represents the combined effect of the shift in vehicle composition from the LEZ and the reduction of total vehicle kilometers traveled from Good Move policies. Finally, we consider a Business-as-Usual (BAU) scenario that assumes no LEZ or Good Move policy implementation beyond 2019, the base year chosen for

9 "Effort Sharing: Member States' Emission Targets: Overview," European Commission, accessed January 12, 2025, https://climate.ec.europa.eu/eu-action/effort-sharing-member-states-emission-targets/overview_en.

10 "Effort Sharing 2021-2030: Targets and Flexibility," European Commission, https://climate.ec.europa.eu/eu-action/effort-sharing-member-states-emission-targets/effort-sharing-2021-2030-targets-and-flexibilities_en.

11 Henrique Morgado Simões and Gregor Erbach, *Roadmap to EU Climate Neutrality – Scrutiny of Member States: Belgium's Climate Action Strategy* (Members' Research Service, December 2024) https://www.europarl.europa.eu/RegData/etudes/BRIE/2024/767175/EPRS_BRI(2024)767175_EN.pdf.

12 "What is Good Move?," City of Brussels, accessed January 3, 2025, https://www.brussels.be/what-good-move.

all of the scenarios.[13] The BAU scenario uses historical survival curves and vehicle electrification percentages from a Vrije Universiteit Brussel study to forecast the vehicle fleet composition over time.[14]

Our study examines the potential GHG benefits of the LEZ and Good Move policies compared with the BAU scenario, assessing how shifts in vehicle fleet composition and a decrease in total vehicle activity contribute to Brussels's GHG reduction targets. Our analysis is confined to vehicle activity within the BCR and captures vehicle kilometers driven within LEZ boundaries by both Brussels residents and commuters who reside outside the city. Leveraging insights from a prior ICCT report that assessed the GHG impact of an LEZ in Warsaw, Poland, our study aims to address a gap in the existing literature by quantifying the life-cycle GHG impact of LEZs, encompassing both direct emissions and indirect effects from upstream emissions.[15]

DATA OVERVIEW

The life-cycle assessment of GHG emissions from vehicles in Brussels comprised two main data sources. We obtained data on direct tailpipe emissions and energy consumption from modeling results that Brussels Environment previously derived for the Brussels vehicle fleet using the European Union's standard vehicle emissions calculator, COPERT version 5.6.1.[16] Developed for official vehicle emissions inventory preparation in European Economic Area member countries, COPERT outputs the emissions and energy consumption associated with ICEVs, hybrid electric vehicles (HEVs), battery electric vehicles (BEVs), and plug-in hybrid electric vehicles (PHEVs) for each scenario considered. Meanwhile, upstream emissions data were compiled through a literature review that drew primarily from three previous ICCT reports: two focused on European passenger cars and heavy-duty vehicles (HDVs) and one on Indonesian two-wheelers.[17] This approach enabled us to the capture the full spectrum of well-to-wheel (WTW) vehicle emissions, which encompass both tank-to-wheel (TTW) emissions associated with the fuel's combustion and well-to-tank (WTT) emissions associated with fuel sourcing, transport, and related factors. The upstream GHG emissions associated with vehicle production, battery production, maintenance, and recycling (when applicable) were included to account for the vehicle's environmental impact over its lifetime (see Table A1).

The COPERT model uses various inputs to capture Brussels's urban conditions, including vehicle stock, average trip length, average vehicle speed, and vehicle survival curves, in addition to the Euro standard and fuel type of each vehicle, to estimate the impact of on-road transport. It can be used to assess the emissions of various vehicle classes, including L-category vehicles, passenger cars, light commercial vehicles (LCVs), heavy-duty trucks (HDTs), and buses.[18] For ICEVs, the model provides tailpipe emissions from fossil fuels segmented by type, including BC, carbon dioxide (CO_2), nitrous oxide (N_2O), and methane (CH_4).[19] Bio-based fuels are credited for CO_2 capture that occurs during plant growth, and the reported tailpipe emissions associated with these fuels are excluded from TTW calculations but are used to estimate fuel consumption and WTT emissions (see Appendix B). For BEVs, COPERT provides the WTT energy consumption, which is then adjusted to account for losses that occur under real-world driving conditions, such as charging losses (see Appendix C).[20]

13 While the LEZ was first implemented in 2018, 2019 was chosen as the base year of the scenarios to avoid any effects relating to COVID-19.

14 Lieselot Vanhaverbeke et al., *Uitrolstrategie voor Laadinfrastructuur in het Brussels Hoofdstedelijk Gewest* [Rollout Strategy for Loading Infrastructure in Brussels Capital Region] (Electrify.Brussels, November 2022), https://leefmilieu.brussels/media/10329/download?inline.

15 Rohit Nepali et al., *Impacts of a Low-Emission Zone on Air Pollutant and Greenhouse Gas Emissions in Warsaw* (TRUE Initiative, November 2023), https://theicct.org/publication/true-warsaw-lez-nov23/.

16 Emisia, "The Industry Standard Emissions Calculator," accessed April 16, 2024, https://copert.emisia.com/.

17 Georg Bieker, *A Global Comparison of the Life-Cycle Greenhouse Gas Emissions of Combustion Engine and Electric Passenger Cars* (International Council on Clean Transportation, 2021), https://theicct.org/publications/global-LCA-passenger-cars-jul2021.; Adrian O'Connell et al., *A Comparison of the Life-Cycle Greenhouse Gas Emissions of European Heavy-Duty Vehicles and Fuels* (International Council on Clean Transportation, 2023), https://theicct.org/publication/lca-ghg-emissions-hdv-fuels-europe-feb23/; Zamir Mera and Georg Bieker, *Comparison of the Life-Cycle Greenhouse Gas Emissions of Combustion Engine and Electric Passenger Cars and Two-Wheelers in Indonesia* (International Council on Clean Transportation, 2023), https://theicct.org/publication/comparison-life-cycle-ghg-emissions-combustion-engine-and-electric-pv-and-2w-indonesia-sept23/.

18 L-category regroups 2- and 3- wheelers and quadricycles in the European Commission's vehicle classification.

19 Black carbon is only accounted for in the vehicle's TTW emissions and not in upstream emissions due to data limitations. All other pollutants are accounted for throughout the other components of the analysis. The emissions are converted to CO_2 equivalents (CO_2e) using the 100-year global warming potential for GHG estimation.

20 COPERT does not provide energy consumption data for non-passenger car BEVs, so we estimated these values by scaling emissions from ICEVs using factors derived from COPERT data or the literature comparing BEVs to fossil fuel counterparts. The selection of factors is based on producing energy consumption values that align most closely with the ICCT Global Transportation Roadmap modeling outputs for the Brussels vehicle fleet; see ICCT, "Roadmap Model Documentation," accessed April 1, 2024, https://theicct.github.io/roadmap-doc/.

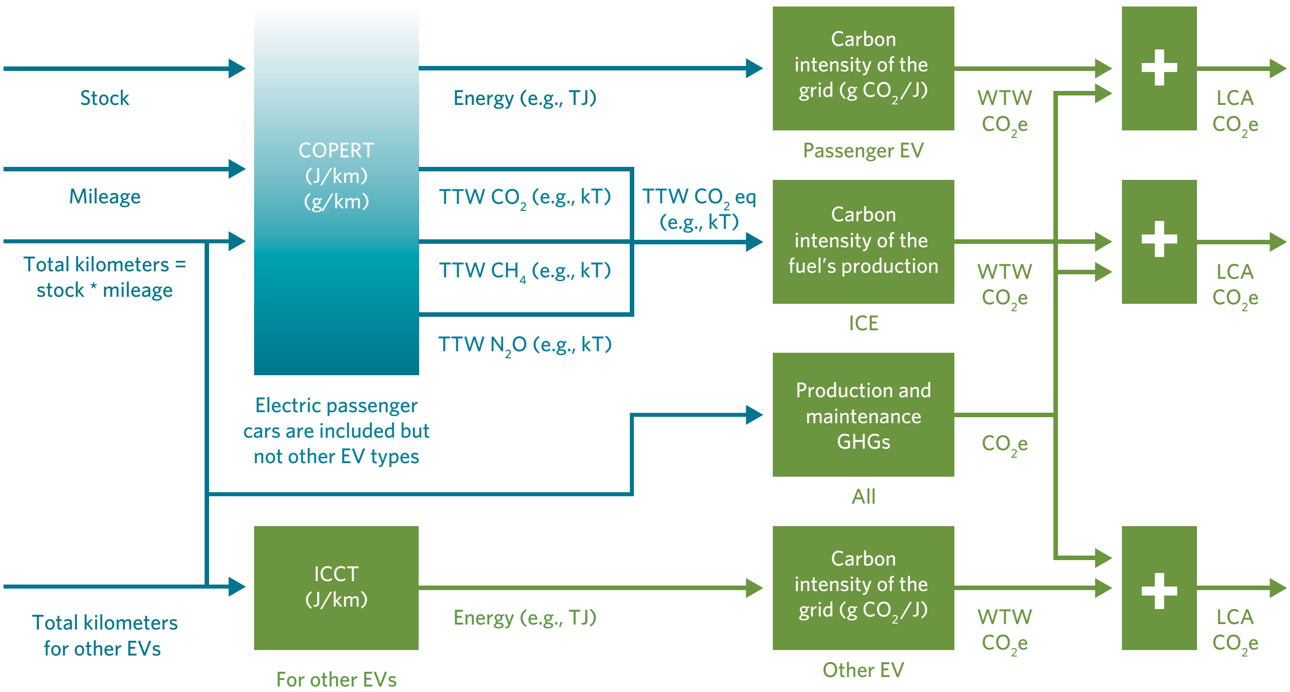

Figure 2. Inputs used to calculate the life-cycle GHG emissions of a vehicle

Following the application of the COPERT calculator, upstream emissions were incorporated to estimate total life-cycle emissions. Figure 2 depicts the different components of upstream emissions, including the carbon intensity of fuel production, the carbon intensity of Belgium's electric grid, vehicle production and maintenance emissions, and losses associated with the transmission and distribution of electricity (see Appendixes A and B).

LIFE-CYCLE ASSESSMENT RESULTS BY FUEL TYPE AND EMISSION SOURCE

In the context of Brussels's LEZ, which implements a phased ban on vehicles of certain fuel types, a comprehensive analysis of life-cycle emissions captures the full scope of vehicle emissions and the environmental impact of various fuel types. This section focuses on passenger cars, which are the most common vehicle category in the BCR and which use a wide range of fuel types, enabling a direct comparison to contextualize the changes in life-cycle emissions related to the LEZ restrictions.

Figure 3 displays the life-cycle emissions per kilometer associated with Brussels's gasoline, diesel, CNG, and LPG ICEVs, gasoline HEVs and PHEVs, and BEVs within the medium-segment passenger car category in the BAU scenario.[21] Life-cycle GHG emissions are categorized by emission source, including the production and transport of fuel or electricity (WTT), fuel consumption during vehicle operation (TTW), and vehicle production and maintenance. The GHG emissions are presented in CO_2e using the 100-year global warming potential for N_2O, CO_2, CH_4, and BC. Additionally, we present the increase in emissions considering the 20-year global warming potential for the short-lived GHGs, BC and CH_4. Averages depicted account for all Euro standards, weighted by their proportion of total activity.

BEVs demonstrated the greatest distance-specific GHG emission reductions, with 4.4 to 6 times lower life-cycle emissions compared with traditional diesel- and gasoline-fueled ICEVs. This equates to 82%–84% lower life-cycle GHG emissions for BEVs compared with gasoline ICEVs. This gap is wider than that estimated in previous studies showing 63%–69% lower average life-cycle GHG

21 The per-kilometer emissions metric is used instead of total emissions in 2025 and 2035 due to uncertainties in vehicle production timing as the fleet evolves, in part because our data do not distinguish between new EVs produced solely to comply with the LEZ, second-hand EVs, or vehicles purchased for other reasons. Per-kilometer emissions for WTT and TTW were derived using outputs from the COPERT model, while those for vehicle and battery production were based on average lifetime kilometers (Appendix). This metric, however, does not capture the significant upfront GHG emissions from production or the emissions savings from EV use outside the LEZ, but still offers valuable insights into the long-term environmental impacts of different fuel types in Brussels.

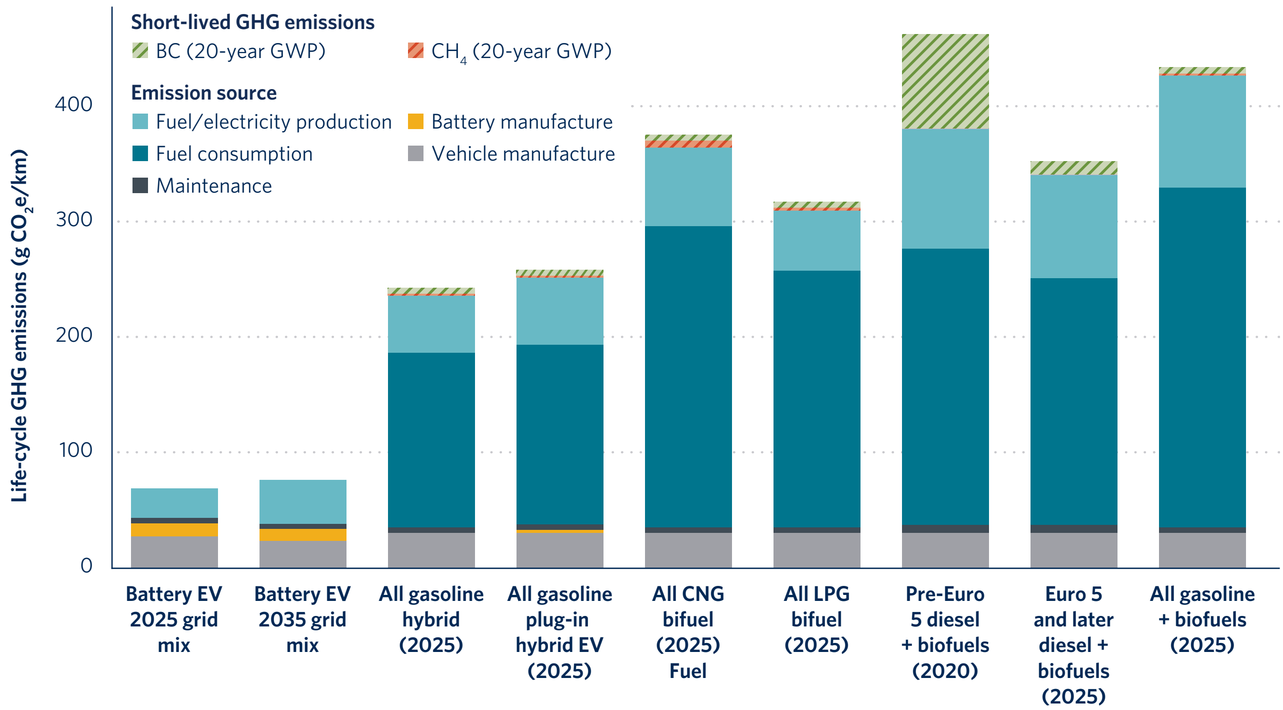

Figure 3. Average life-cycle GHG emissions per kilometer in the BAU scenario for medium-segment passenger cars driven in Brussels, by fuel type and emission source

emissions for BEVs in Europe.[22] The wider gap between BEVs and gasoline ICEVs in our study is likely influenced by two factors. First, the extent of the gap varies significantly between countries, as it is largely determined by the composition of the electric grid. Belgium's electric grid has a lower carbon footprint because of its significant share of nuclear power (Appendix B), resulting in BEV emissions around 10% lower than the European average. Second, COPERT produces higher TTW CO_2 estimates under the low vehicle speeds (21.8 km/h) used as inputs to reflect Brussels's urban driving conditions, which further amplifies the advantage of BEVs.[23]

The emissions of BEVs in Brussels are largely contingent on both the carbon intensity of the electric grid and battery component sourcing. Despite a slight increase in BEV WTT emissions in 2035 due to a more carbon-intensive electric grid from the closure of Belgium's two remaining nuclear plants, BEVs still emit 57% lower electricity production emissions compared with the fuel production emissions associated with diesel and 60% lower than those associated with gasoline, which are assumed to change minimally compared with the 2025 values. In our projections for battery production from 2030 onwards, we anticipate a 20% increase in battery capacity, which is coupled with a 20% decrease in emissions relating to battery sourcing driven by technological advancements. Importantly, these changes are expected to balance each other. Spread over the lifetime of the vehicle, BEV production emissions, while initially more carbon intensive than those of ICEVs, do not significantly increase the vehicle's environmental footprint.

Diesel-fueled cars, on average, exhibit lower life-cycle emissions than gasoline cars, with a noteworthy exception being diesel cars certified to pre-Euro 5 emission standards. Beginning with Euro 5, diesel vehicles were equipped with a diesel particulate filter, which is a vehicle aftertreatment system used to significantly reduce PM emissions. BC, a component of PM, is considered a critical short-lived GHG with an exceptionally high 20-year global warming potential value of approximately 2,420.[24] Highlighting the 20-year warming potential underscores

22 Bieker, *A Global Comparison*.

23 Under such driving conditions, COPERT calculates the average fuel consumption as 12.7 L/100 km for gasoline and 9.1 L/100 km for diesel passenger cars (see Appendix).

24 A 20-year global-warming potential indicates that BC contributes to global warming at a rate 2,420 times higher than CO_2 over a period of 20 years from the time the pollutant is released into the atmosphere. See Gunnar Myhre et al., "Anthropogenic and Natural Radiative Forcing - Supplementary Material," in *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, ed. Thomas F. Stocker et al. (Intergovernmental Panel on Climate Change, 2013), https://www.ipcc.ch/site/assets/uploads/2018/07/WGI_AR5.Chap_.8_SM.pdf.

the urgency in addressing vehicles with high BC emissions: Pre-Euro 5 diesel vehicles showed an additional 82 grams of CO_2e per kilometer driven compared with post Euro-5 models, making them the highest emitting category, at 462 grams of CO_2e per kilometer.[25]

In Brussels, both gasoline and diesel fuels contain 10.7% biofuels by volume, with the diesel mix surpassing the EU norm of 7% biofuels. The higher concentrations of hydrotreated vegetable oil and fatty acid methyl ester in the diesel mix, while mitigating TTW emissions, lead to elevated WTT emissions, which account for approximately 29% of WTW emissions of vehicles driven in Belgium. Biodiesel derived from food-based feedstocks—notably rapeseed, palm, and soybean oil, all key components in the EU mix—have production emissions that surpass the total life-cycle emissions of fossil diesel when accounting for indirect land-use change (ILUC).[26]

Other fuel alternatives, such as CNG bi-fuel and LPG bi-fuel, yield minimal reductions in life-cycle emissions. Gasoline PHEVs and gasoline HEVs exhibit approximately 43% lower life-cycle emissions than traditional gasoline vehicles, with gasoline PHEVs showing slightly higher emissions than gasoline HEVs. This is because the modeled electricity consumption and fossil fuel emissions were weighted to reflect our assumption that PHEVs drive on electricity only 47% of the time, primarily due to depleted batteries.[27] However, PHEVs do have the potential to transition certain ICEV segments, like HDVs not currently subject to full bans under the LEZ, to zero-tailpipe emission vehicles. In this regard, some researchers have expressed support for geofencing that would automatically switch these vehicles to electric mode in LEZs or other defined areas to encourage greater emission reductions—though verifying the proper use of geofencing remains a significant challenge in reducing vehicle emissions.[28]

The decision to phase out pre-Euro 5 vehicles in 2022, followed by all diesel and gasoline vehicles in 2030 and 2035, aligns with the substantial emissions reductions achievable through the adoption of alternative fuels, as explored in the next section.

LIFE-CYCLE GHG IMPACT OF THE LEZ

Figure 4 illustrates the annual contributions of various vehicle types to the overall GHG emissions in Brussels under the BAU scenario.[29] Notably, passenger cars, the primary focus of the LEZ, emerge as the leading contributors, accounting for 63%–69% of annual emissions from 2019 to 2040. LCVs are the second-largest source of emissions until 2033, when they are surpassed by HDTs. Buses maintain a steady share of emissions, ranking fourth throughout the period, followed by L-category vehicles.

25 The 20-year global warming potential values for BC and CH_4 represent the excess emissions relative to the 100-year global warming potential, which is already included in TTW emissions.

26 Bieker, *A Global Comparison*.

27 Patrick Plötz et al., *Real-World Usage of Plug-in Hybrid Vehicles in Europe: A 2022 Update on Fuel Consumption, Electric Driving, and CO2 Emissions* (International Council on Clean Transportation, 2022), https://theicct.org/publication/real-world-phev-use-jun22/.

28 Philipp M. Haaf, Manuel Wiener, and Maren Aurich, "Benefits of Combining PHEVs and Geofencing," *Capgemini* (blog), March 23, 2021, https://www.capgemini.com/insights/expert-perspectives/benefits-of-combining-phevs-and-geofencing/.

29 Importantly, in the LEZ and LEZ + Good Move scenarios, the share of emissions from passenger cars decreases over time due to accelerated electrification, highlighting the effectiveness of targeting this vehicle category.

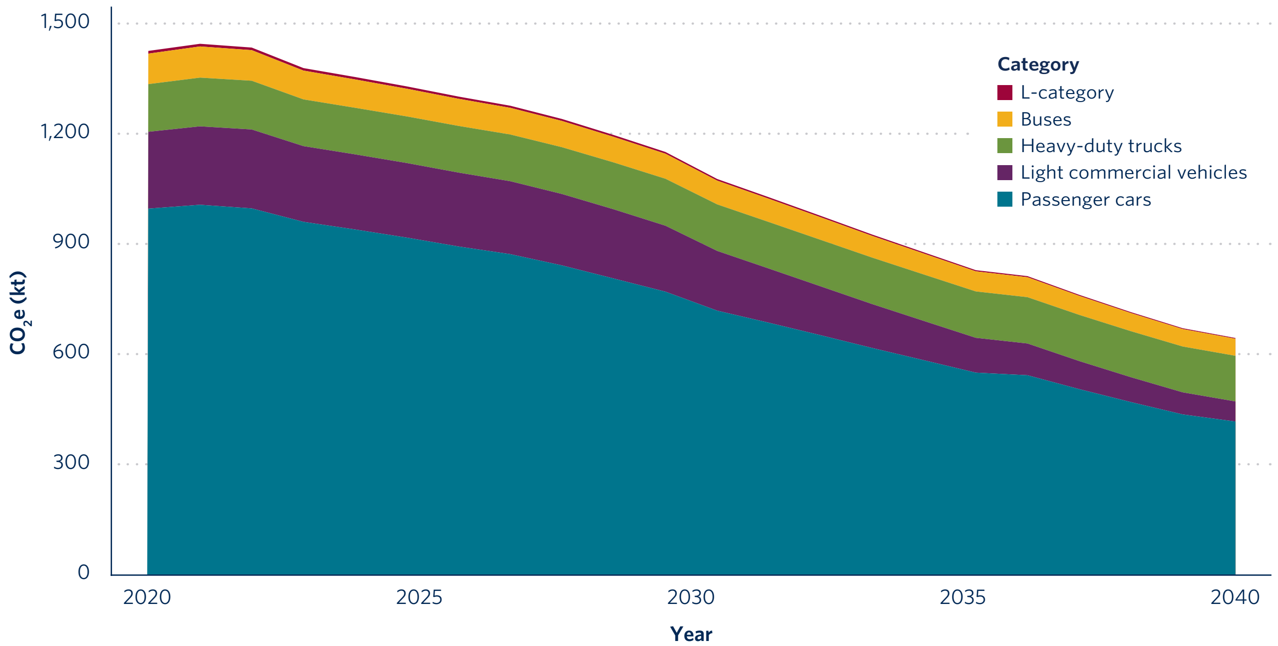

Figure 4. Annual life-cycle GHG emissions from various vehicle categories in Brussels over time with natural fleet turnover in the BAU scenario

Figure 5 highlights how the proportion of direct (i.e., TTW) and upstream (i.e., WTT and production) emissions shift across different scenarios reflecting the changing fleet composition over time. In 2020, direct emissions account for two-thirds of the total transport emissions in the BCR under the BAU scenario. By 2040, these direct emissions still represent more than half of the overall emissions. However, with the accelerated adoption of electric vehicles driven by the LEZ restrictions, the LEZ and LEZ + Good Move scenarios show a comparatively rapid rise in the share of upstream emissions, which exceed 70% of total emissions by 2040. This trend underscores the growing significance of vehicle production, battery production, and electricity sourcing in emission reductions as the vehicle fleet transitions under these mobility policies.

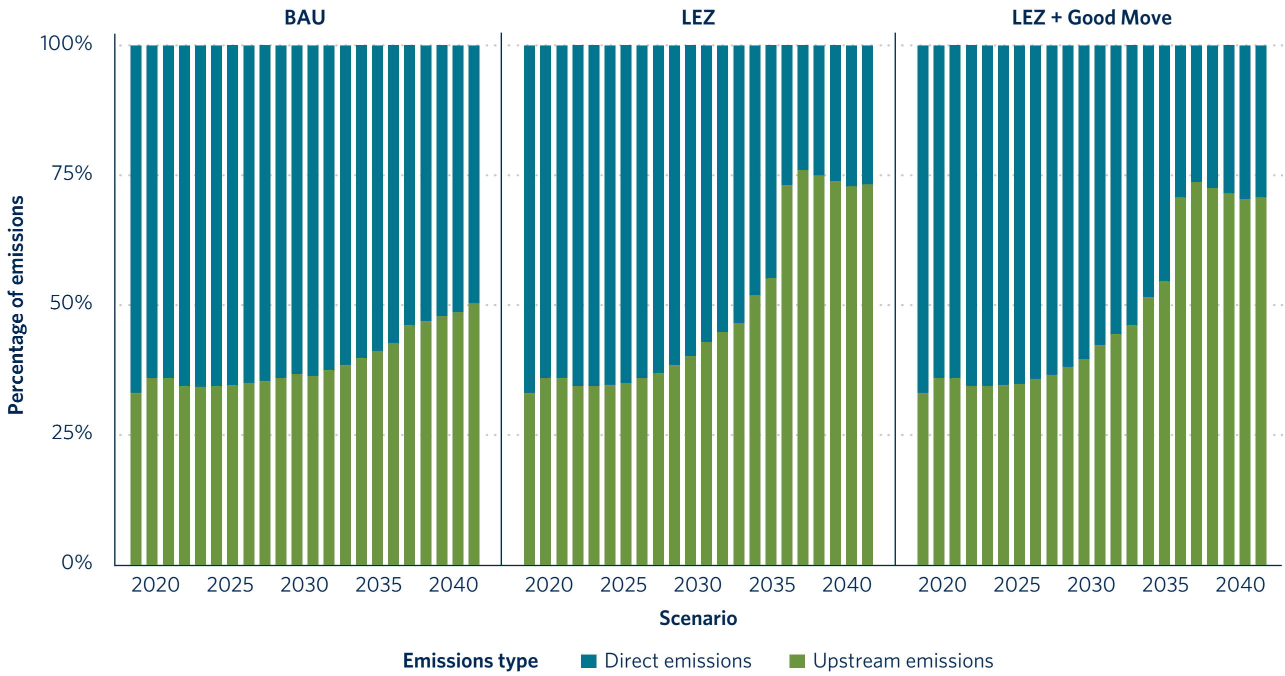

Figure 5. Annual shares of direct and upstream emissions by scenario

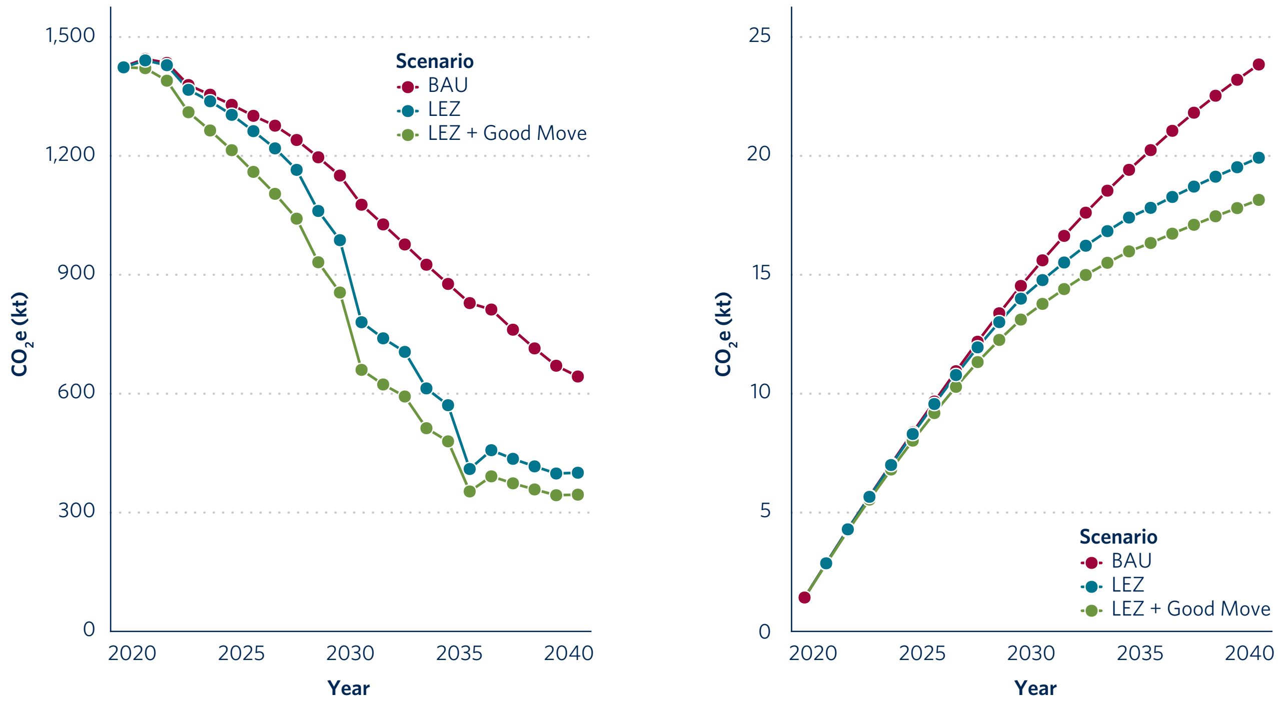

Figure 6. Annual life-cycle GHG emissions (left) and cumulative life-cycle GHG emissions with a base year of 2019 (right) for each proposed scenario

When evaluating the overall impact of the LEZ, it is crucial to delve into both the annual and cumulative emissions across different scenarios. Figure 6 illustrates both of these trends, highlighting the significance of the LEZ restrictions in reducing GHG emissions from diesel and gasoline vehicles.

Projected annual emissions decline by about 56 kt between 2019–2021 and 2022 across all scenarios, primarily attributable to the decrease in BC associated with the use of diesel particulate filters. In 2022, Brussels implemented city-wide driving restrictions on Euro 4 diesel vehicles, prohibiting the use of pre-Euro 5 diesel passenger cars, LCVs, and buses.[30] After 2022, emissions continue to decline at a slower rate due to a combination of natural fleet turnover and subsequent smaller restrictions by Euro standard across segments. The years 2030 and 2035 are pivotal for emissions reduction in the LEZ and LEZ + Good Move scenarios due to LEZ measures that ban diesel and gasoline passenger cars, LCVs, and L-category vehicles. In 2030, the reductions in GHG emissions compared with the BAU scenario are 27% for the LEZ scenario and 39% for the LEZ + Good Move scenario. By 2035, these reductions intensify to 50% for the LEZ scenario and 57% for LEZ + Good Move scenario.

Among other policy implications, by 2030, the LEZ and LEZ + Good Move scenarios align with Belgium's goals under the EU Effort Sharing Regulation. As noted above, despite a modest reduction of only 8% in transportation GHG emissions from 2005 to 2023, Belgium aspires to achieve a 47% all-sector reduction below 2005 levels by 2030, primarily via development of electromobility and fiscal incentives for clean vehicles. Within this framework, Brussels—which has set regional objectives to match the national GHG targets—demonstrates significant progress in the LEZ and LEZ + Good Move scenarios, achieving annual emission reductions of 45% and 54% by 2030, respectively, compared with 2019. The BAU scenario lags with only a 24% reduction by 2030. The LEZ + Good Move Scenario, in particular, positions Brussels to cut transportation emissions at over double the rate of the BAU scenario and exceed the all-sector GHG target. These results emphasize the importance of the city's initiatives in reducing emissions from the transportation sector, which accounted for almost a quarter of Belgium's total emissions in 2023.[31]

By 2035, the projection anticipates 97% of all light vehicles will be battery electric in the LEZ and LEZ + Good Move scenarios, while fewer than 50% of vehicles will be battery electric under the BAU scenario assuming natural

30 "Low Emission Zone: New Ban Since 2022," City of Brussels, accessed January 12, 2025, https://www.brussels.be/low-emission-zone-new-ban-2022.

31 Simões and Erbach, *Roadmap to EU Climate Neutrality*.

fleet turnover. The annual declines in GHG emissions in all scenarios primarily stem from the reduction in TTW emissions attributable to the transition from fossil-fueled vehicles to BEVs.

By 2040, annual emissions reductions in the LEZ and LEZ + Good Move scenarios are projected to range between 72% and 76% below 2019 levels, contrasting with the BAU scenario's comparatively modest 56% reduction.[32] Considering cumulative emissions reductions, the LEZ and LEZ + Good Move scenarios avoid an additional 3.9 and 5.7 Mt of emissions, respectively, by 2040 in comparison with the BAU scenario.[33] Good Move policies account for the additional 1.8 Mt in GHG reductions under the LEZ + Good Move.

SENSITIVITY ANALYSIS OF LEZ IMPACT USING REMOTE SENSING DATA

We next performed a sensitivity analysis of the projected LEZ impacts on passenger car emissions using vehicle information from an ICCT remote sensing (RS) campaign conducted in 2020 in the BCR.[34] In this section, we explore observed differences in vehicle performance under low speeds from the COPERT model data, on which this study is based, and those inferred from the 2020 RS campaign data, which represent vehicles operating under real-world conditions. This allows us to evaluate whether the projected effect of the LEZ is sustained under different assumptions regarding a vehicle's fuel consumption, a key component in determining TTW and WTT emissions for ICE vehicles.

Each passenger car measured in the RS data was categorized into either mini, small, medium, or large segments using the engine displacement cutoffs defined by Emisia.[35] The breakdown by segment of the unique vehicles captured in the RS data aligns closely with the COPERT vehicle stock, with over half of the vehicles in the medium segment and around one-third in the small segment, as displayed in Table 1. The methodology used to derive tailpipe emissions from the RS data can be found in Appendix D.

Figure 7 displays the total annual and cumulative GHG emissions from passenger cars based on the RS data versus the COPERT data as the foundation for determining tailpipe emissions. While overall emissions decreased across all scenarios due to the lower fuel consumption indicated by the RS data, the relative impacts of the LEZ and LEZ + Good Move scenarios remain consistent. By

Table 1. Passenger car composition by segment and mean distance-specific tailpipe emissions by segment and fuel type for each data source

	Data collected during the remote sensing campaign (2020)			COPERT (2020)		
	Percentage of unique passenger cars	Mean urban tailpipe emissions (g CO_2/km)		Percentage of stock composition	Mean urban tailpipe emissions (g CO_2/km)	
		Gasoline	Diesel		Gasoline	Diesel
Mini	0.14%	160	117	0.4%	218	150
Small	30.9%	178	151	36.0%	269	228
Medium	60.6%	212	177	55.6%	308	228
Large	7.7%	322	230	8.0%	446	313

32 These 2040 projections should be interpreted as indicative trends, given uncertainties in predicting how mobility patterns and policies might evolve beyond 2035 for the LEZ and beyond 2030 for Good Move.

33 Values for 2040 do not fully capture production emissions, which this study accounts for on a per-kilometer-driven basis but in reality are entirely emitted in the year of production. However, given that TTW and WTT emissions account for the majority of vehicle emissions, this estimate still effectively highlights the substantial emissions reductions realized through the LEZ and Good Move policies.

34 Yoann Bernard et al., *Evaluation of Real-World Vehicle Emissions in Brussels* (International Council on Clean Transportation, 2021), https://www.trueinitiative.org/publications/reports/evaluation-of-real-world-vehicle-emissions-in-brussels. Our sensitivity analysis compares the impacts of the LEZ on passenger car emissions due to limited data capture from other vehicle categories in the RS data.

35 "COPERT Documentation," Emisia, accessed November 18, 2024, https://copert.emisia.com/copert/documentation/.

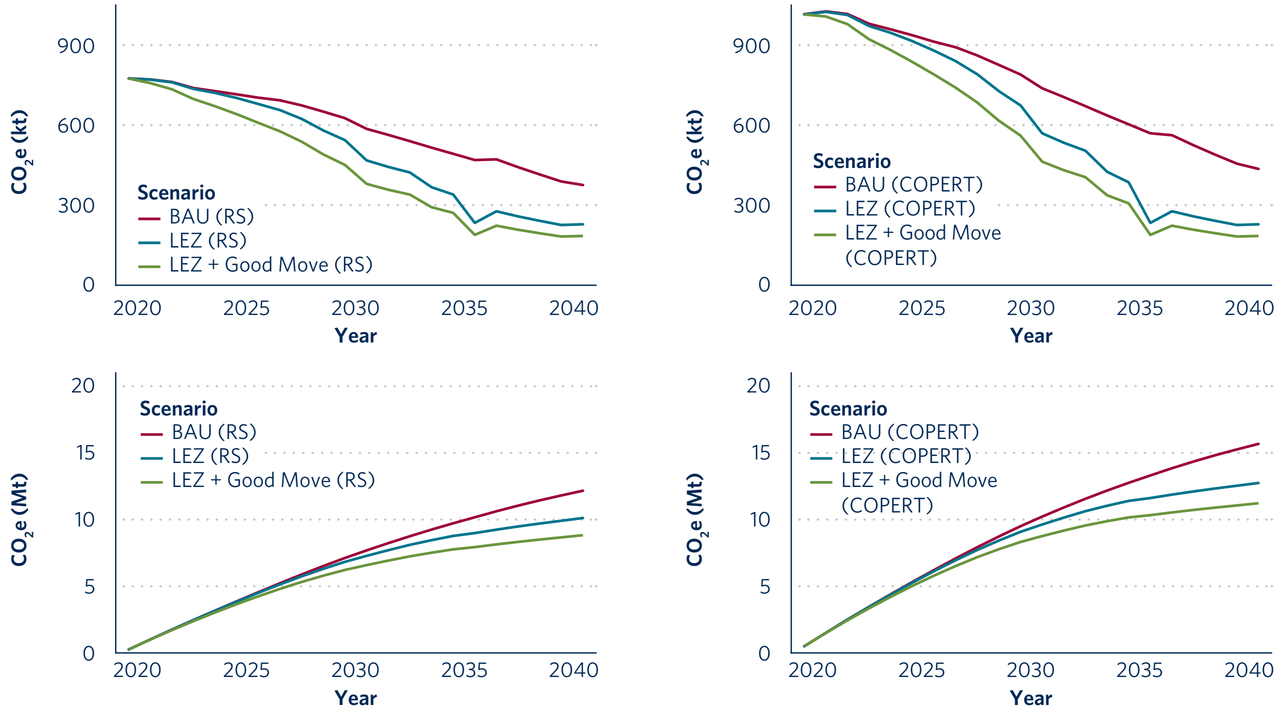

Figure 7. Annual and cumulative GHG emissions by scenario and year using RS data (left) and COPERT data (right)

2040, cumulative emission reductions are projected to be 18% for the LEZ scenario and 27% for the LEZ + Good Move scenario compared with the BAU scenario using the COPERT analysis. Using the RS data, these reductions are 16% for the LEZ scenario and 26% for the LEZ + Good Move scenario. For both the RS and COPERT data, the most significant emission reductions occur during the LEZ vehicle phaseouts in 2030 and 2035, demonstrating the continued efficacy of the LEZ interventions across different data sources. This sensitivity analysis further suggests that the LEZ delivers substantial GHG reductions independent of different fuel consumption assumptions and despite differences in absolute GHG emissions.

OPPORTUNITIES TO STRENGTHEN THE BRUSSELS LEZ

This section presents the results of additional scenarios that evaluate potential changes in Brussels's LEZ schedule, such as different assumptions about Belgium's electric grid and additional vehicle restrictions and policies. These scenarios aim to study the sensitivity to the projected carbon intensity of the grid and explore ways in which the LEZ could be strengthened to yield additional reductions in GHG emissions and accelerate vehicle electrification. These scenarios model: (1) the accelerated closure of all of Belgium's nuclear plants, (2) the introduction of a weight tax on large-segment passenger vehicles in 2024, and (3) the implementation of a restriction of Class N2 HDTs in 2035.[36]

SCENARIO 1: ACCELERATED CLOSURE OF ALL OF BELGIUM'S NUCLEAR PLANTS

Although Belgium had initially planned to phase out all nuclear power by 2025, a final agreement signed with the Belgian government in December 2023 extended the operation of the Tihange 3 and Doel 4 nuclear reactors from November 2025 to 2035.[37] This extension effectively reduces the carbon intensity of the grid for a decade. To explore the potential impact of higher-carbon energy sources for electricity production on the effectiveness of the LEZ, we modeled a scenario in which electricity produced by these nuclear power plants is replaced with gas between 2025 and 2035.

36 Class N2 HDTs refer to medium-sized commercial vehicles with a maximum weight of up to 12 tons.

37 "ENGIE Signs a Final Agreement with the Belgian Government on the Extension of the Tihange 3 and Doel 4 Nuclear Reactors," press release, ENGIE, December 13, 2023, https://newsroom.engie.com/actualites/engie-signe-un-accord-final-avec-le-gouvernement-belge-sur-la-prolongation-des-reacteurs-nucleaires-tihange-3-et-doel-4-594b-ff316.html.

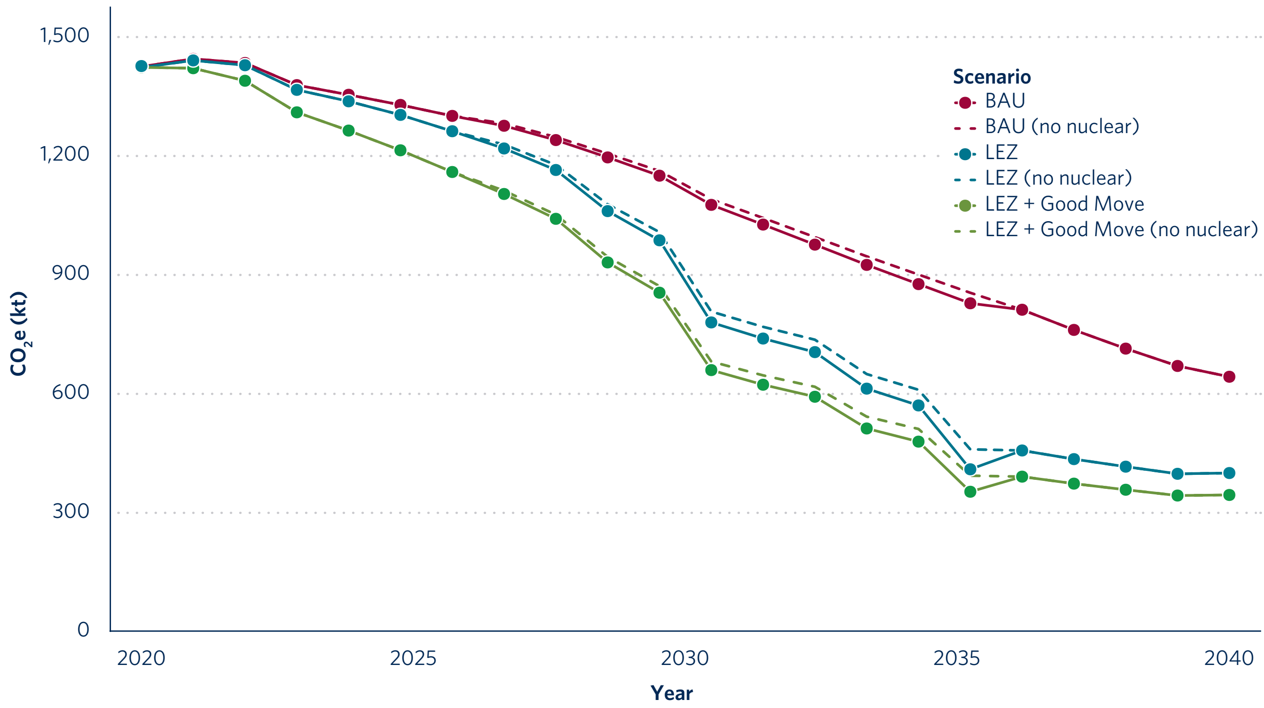

Figure 8. Annual GHG emissions from all vehicles in Brussels with and without the nuclear plant closures from 2025 to 2035

As illustrated in Figure 8, this assumption results in an increase in the carbon intensity of the grid by nearly one-third from 2025 to 2035. Even with the increased grid carbon intensity, the cumulative emissions rise by only 1.2% and 1.4% for the LEZ + Good Move and LEZ scenarios, respectively, by 2040. This slight increase highlights that the reduction in WTT and TTW emissions from transitioning to BEVs offsets the impact of higher-carbon electricity. In other words, the phaseouts of ICEVs are sufficiently strong to ensure that BEVs, even under a more carbon-intensive grid, still lead to lower emissions compared with fossil-fueled vehicles.

SCENARIO 2: WEIGHT TAX ON LARGE-SEGMENT PASSENGER CARS

The second scenario introduces a hypothetical weight tax on large-segment passenger vehicles in 2025 to the LEZ, inspired by a recent initiative in Paris that tripled parking charges for SUVs to mitigate vehicle pollution and enhance safety for non-vehicle commuters.[38] In this scenario, we assume that a tax on large-segment vehicles would encourage 25% of large passenger vehicle owners to transition to medium-segment passenger vehicles. While, on average, medium-segment passenger cars are driven less than large-segment passenger cars, we assume that individuals making this switch will maintain their driving habits. In other words, the additional medium passenger cars are modeled as being driven the same distance as large-segment cars.[39]

On average, the TTW emissions of a medium-segment passenger car are 27% lower (for diesel vehicles) and 31% lower (for gasoline vehicles) than those of large-segment passenger car counterparts, implying lower WTT emissions as well. If implemented in 2025, this policy would additionally reduce cumulative passenger car GHG emissions by 88 kt and 71 kt in the LEZ and LEZ + Good Move scenarios, respectively, reductions of around 1% each compared with the original scenarios without a weight tax. This level of emissions is roughly equivalent to the GHG emissions from 2,100–2,600 gasoline vehicles in Brussels.[40]

38 Wilma Dragonetti, "Space Is for Parisians, Not SUVs," *Euro Cities*, February 9, 2024, https://eurocities.eu/latest/space-is-for-parisians-not-suvs/.

39 To calculate the additional GHG emissions from medium-segment cars, we adjusted their vehicle production GHG emissions by applying the relative difference between the distances driven by medium- and large-segment cars to account for the longer distance driven by large-segment cars during the vehicle's lifetime.

40 Annual GHG equivalencies were calculated using the following equation: * . Annual vehicle kilometers traveled (VKT) were calculated using a stock-weighted average of mean passenger car annual activity from COPERT, and CO_2/km was calculated based on the average life-cycle GHG emissions per kilometer for medium-segment gasoline passenger cars driven in Brussels in 2025 in the BAU scenario. "Total GHG" represents the cumulative emissions reductions over the years of policy implementation.

SCENARIO 3: 2035 BAN ON CLASS N2 HEAVY-DUTY TRUCKS

In the final scenario, depicted in Figure 9, we assume a restriction on Class N2 diesel vehicles in the LEZ and LEZ + Good Move scenarios. Currently, the LEZ restriction schedule does not include a full ban of ICE HDTs, which are projected to account for the second-largest share of emissions by 2030 in both the LEZ and LEZ + Good Move scenarios. In 2035, the EU stock share of electric Class N2 vehicles is expected to reach 48%, indicating significant market penetration.[41] Assuming that the N2 restriction begins in 2035, by 2040, there is an additional 2.4% projected decrease in annual HDT emissions (3.5 kt, or equivalent to the GHG emissions from 1,650 gasoline cars in Brussels) compared with the LEZ and LEZ + Good Move scenarios without the ban.[42] In this regard, imposing a ban on a class of HDTs would not only help achieve further GHG reductions but also spur progress toward electrifying these vehicles, which are projected to account for 32%–35% of total vehicle emissions in 2040.

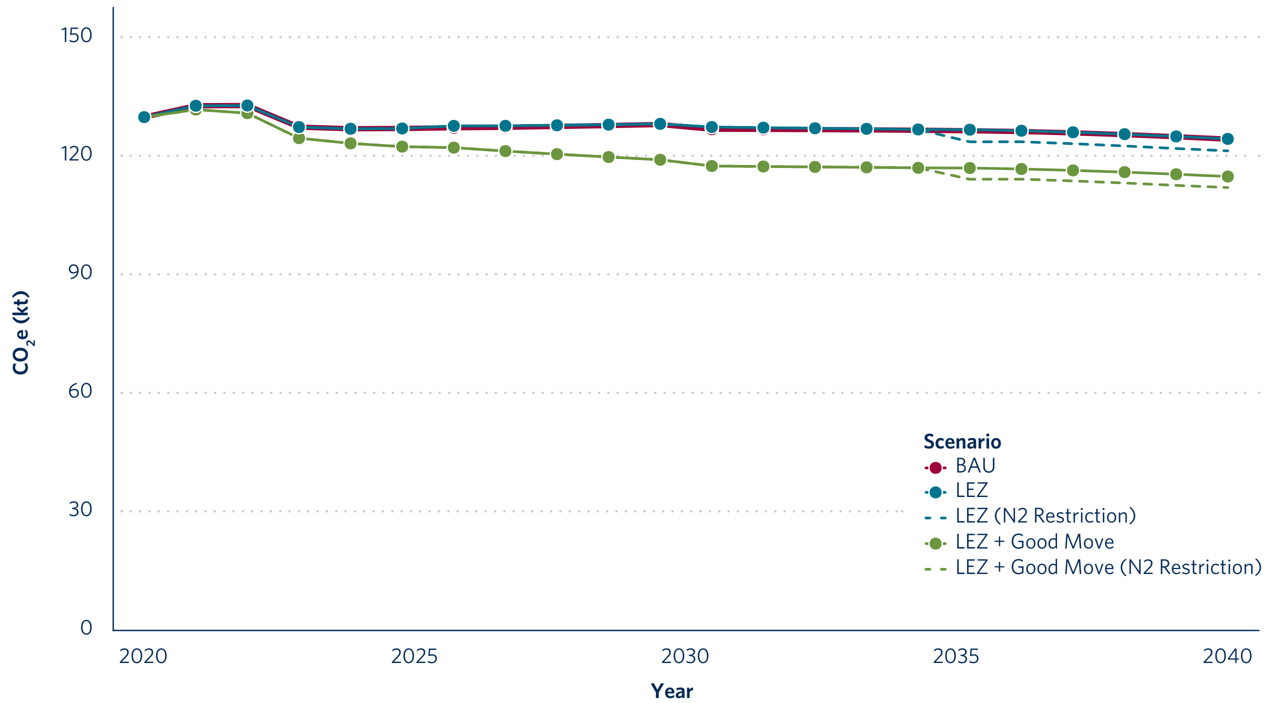

Figure 9. Annual GHG emissions from HDVs in Brussels with and without the additional N2 restriction

41 Eamonn Mulholland and Felipe Rodríguez, *An Analysis on the Revision of Europe's Heavy-Duty CO_2 Standards* (International Council on Clean Transportation, May 22, 2023), https://theicct.org/wp-content/uploads/2023/05/europe-heavy-duty-vehicle-co2-standards-may23.pdf.

42 See footnote 40 for this calculation.

IMPACT OF LEZ DELAYS ON LIFE-CYCLE GHG IMPACT

As the analysis above was conducted prior to the Brussels Regional Parliament's decision to delay the 2025 step of LEZ regulations to 2027, we additionally examine the impact of this 2-year delay on cumulative life-cycle GHG emissions (designated in Figure 10 as "2025 -> 2027 Shift"). We also consider a scenario in which all planned LEZ measures are delayed by 2 years, given the possibility of additional delays in the future ("Full +2 Shift" in Figure 10).

To calculate cumulative emissions, we first derived a scenario-specific scaling factor reflecting the change in cumulative tailpipe emissions from the delay compared with the original LEZ schedule.[43] The cumulative life-cycle emissions for the altered schedule were then estimated by applying these factors to the cumulative life-cycle emissions estimated for the original LEZ schedule. The results suggest that the confirmed 2-year delay of the planned 2025 LEZ restrictions would have a limited effect on cumulative life-cycle GHG emissions, assuming the remaining LEZ measures are unaffected. However, this delay has a more substantial impact on projected pollutant emissions directly related to air quality and health. A prior study by the TRUE Initiative identified Euro 5 diesel cars as responsible for the largest share of NO_x emissions in real-world conditions in Brussels, accounting for approximately 40%–50% of light-duty NO_x emissions.[44] Additionally, Brussels Environment has estimated that a 2-year delay of the 2025 step would result in NO_x levels exceeding the EU limit of 20 µg/m^3 on 8% of roads.[45]

When analyzing the life-cycle GHG impact of delaying all future LEZ measures by 2 years, the effects become significant. Between 2019 and 2040, reductions in cumulative GHGs compared with the BAU scenario would drop to 3.9% for the LEZ scenario and 11.5% for the LEZ + Good Move scenario, compared with the original 15.6% and 23.2% reductions. Even if Good Move policies were fully implemented in a full 2-year delay scenario, life-cycle GHG reductions would fall short of the reductions from the initial LEZ schedule without Good Move. This is largely due to the missed cumulative emission savings from the planned bans on ICEVs in 2030 and 2035. This sensitivity analysis highlights that any further delays, including to the upcoming phaseouts of diesel and gasoline vehicles, would significantly hinder Brussels's progress toward achieving its emissions reduction goals.

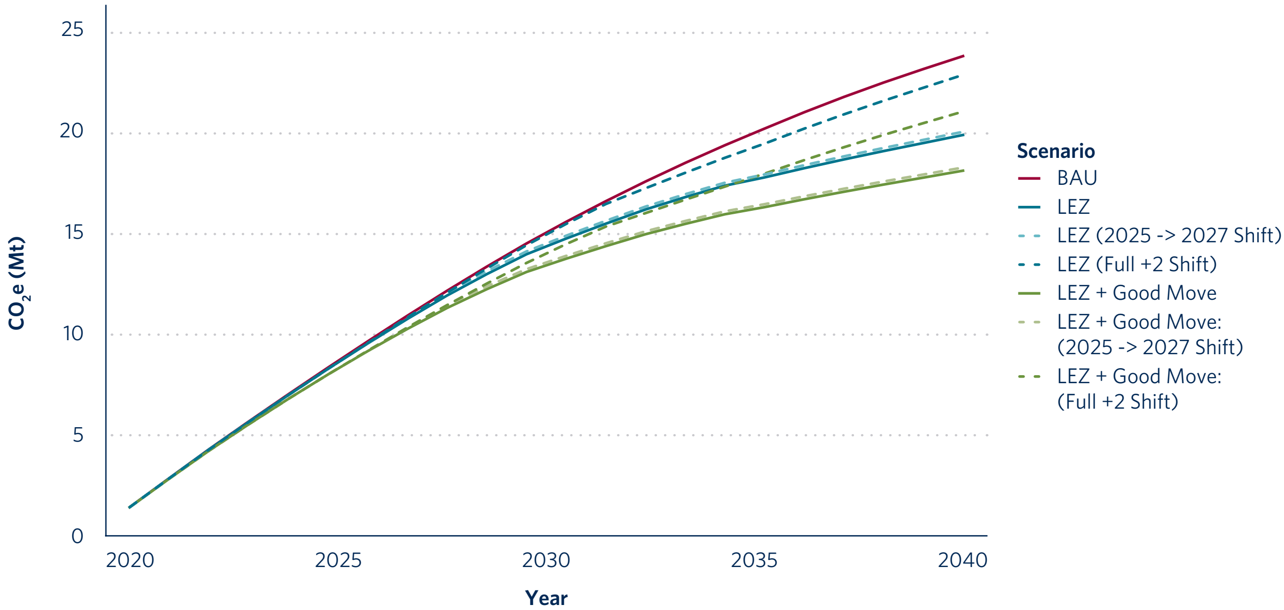

Figure 10. Cumulative life-cycle GHG emissions with and without a shift in the next phase of LEZ regulations from 2025 to 2027 and a full 2-year shift of all proposed LEZ measures

43 Modified COPERT outputs reflecting the impacts on tailpipe emissions associated with the altered LEZ schedules were provided by Brussels Environment.

44 Bernard et al., *Evaluation of Real-World Vehicle Emissions in Brussels.*

45 TRUE Initiative, "TRUE Data Exposes Threat of Delaying Brussels LEZ," October 2, 2024, https://www.trueinitiative.org/news/2024/october/true-data-exposes-threat-of-delaying-brussels-lez.

CONCLUSION

This study modeled three policy scenarios between 2019 and 2040 and found that the two Brussels LEZ scenarios—one modeling the implementation of the LEZ as initially planned and the other considering the LEZ alongside measures under the Good Move plan—result in cumulative GHG emission reductions of 3.9–5.7 Mt by 2040, equivalent to the GHG emissions from 83,000–121,000 gasoline cars in Brussels.[46] Overall, this study underscores the potential of an LEZ to expedite the transition toward less-polluting transportation in Brussels and help meet the city's air quality and climate goals. Conclusions that can be drawn from this study, along with policy recommendations that the city could consider, are described below.

The LEZ in Brussels could help to substantially reduce life-cycle GHG emissions from on-road vehicles and accelerate the EV transition. Our study estimates that the implementation of the LEZ in Brussels could lead to a 50% reduction in annual GHG emissions by 2030 for the LEZ + Good Move scenario and by 2032 for the LEZ scenario compared with 2019 levels. Both LEZ scenarios position Brussels to achieve its goal of a 47% reduction in all-sector GHG emissions by 2030 under the EU Effort Sharing Regulation. These scenarios also show a 97% EV penetration by 2040, in contrast to just under a 50% EV penetration in the BAU scenario, further highlighting the role the LEZ could play in accelerating the EV transition.

Investing in a robust mobility framework to promote non-car-based modes of transportation can accelerate emission reductions. Our results suggest that prioritizing non-car-based transportation is effective for accelerating emissions reduction, with the LEZ + Good Move scenario showing a substantial decrease in passenger vehicle stock, of 21% by 2030. The decrease in car traffic results in an additional 1.8 Mt of cumulative GHG emission reductions in the LEZ + Good Move scenario compared with the LEZ scenario.

A more ambitious LEZ design could generate more immediate reductions in GHG emissions. While the most significant projected emission reductions are observed with the phaseout of diesel and gasoline cars in 2030 and 2035, a tax on large-segment passenger cars could encourage a shift to medium-segment passenger cars, which have 31% lower TTW emissions on average. If 25% of passengers switched from large-segment to medium-segment vehicles starting in 2025, the estimated emissions savings by 2040 would be equivalent to removing the GHG emissions from roughly 2,300 gasoline cars in Brussels over the same period.

Future actions to address GHG emissions could target heavy-duty vehicles and coaches as technology evolves and innovative solutions are implemented. While our analysis projects observed annual reductions in GHG emissions ranging from 79% to 83% in 2040 compared with 2019 levels, the LEZ schedule leaves emissions from fossil-fueled coaches and HDTs largely unaddressed. Our study estimates that banning N2 HDTs beginning in 2035 would result in a 2.4% decrease in annual HDT emissions, equivalent to the GHG emissions from 1,650 gasoline passenger vehicles in Brussels. This ban would represent an initial step toward reducing emissions from HDTs and would be aligned with the projected increase in EV penetration within this vehicle class.

46 See footnote 40 for this calculation.

APPENDIX A: VEHICLE CYCLE EMISSIONS

PASSENGER CARS AND LIGHT COMMERCIAL VEHICLES

Table A1 describes the scope of emissions captured from vehicle manufacture, maintenance, and battery manufacture. Tables A2 and A3 depict the per-kilometer GHG emissions from vehicle manufacture, maintenance, and battery manufacture for BEV and ICEV passenger cars. These values are based on an ICCT study focused on ICEV and BEV passenger cars in Europe.[47] A key adjustment from this previous life-cycle assessment (LCA) involves assumptions regarding battery production carbon intensity. Like the earlier study, we assume that NMC-622 is the dominant battery chemistry until 2030, rather than NMC-811, which is commonly modeled. However, the carbon intensities for these chemistries have been updated using the 2023 Greenhouse gases, Regulated Emissions, and Energy use in Technologies (GREET) model, and the regional market shares for 2023 batteries have been revised with International Energy Agency data.[48] For 2030 and onwards, market shares are conservatively estimated at 75% from Europe and 25% from China, although a 2024 ICCT study suggests that Europe's projected market demand could fully meet regional supply, potentially leading to 100% regional production and a further reduction in 2030 carbon intensities.[49]

Vehicle manufacturing emissions estimates are presented in grams of CO_2e per kilometer and are obtained by dividing the glider and powertrain manufacturing emissions by the total kilometers driven over the lifetime of the vehicle. Notably, the vehicle weight used for calculating vehicle manufacturing emissions does not include the battery. For ICEVs, the same vehicle weights are used for the manufacturing calculation but the 2021 manufacturing emissions are higher, at 5.2 t CO_2e/t vehicle compared with 4.7 t CO_2e/t vehicle for BEVs. For both BEVs and ICEVs, it is assumed that vehicle manufacturing emissions will decrease by 15% in 2030.

Battery manufacture GHG emissions are calculated by multiplying the battery capacity by the average battery's carbon intensity and dividing by the distance traveled over the car's lifetime. In 2030, it is assumed that the battery capacity will increase by 20% and the carbon intensity of the average battery used will decrease by 20%.

For BEVs, maintenance emissions are 5 g CO_2e/km in 2021, decreasing to 4 g CO_2e/km in 2030. For diesel vehicles, maintenance emissions are 7 g CO_2e/km due to urea, while for all other vehicle types, maintenance emissions are 5 g CO_2e/km.

Table A1. Scope of GHG emissions considered in the vehicle cycle

Glider and powertrain	• Production of the vehicle, including raw material extraction and processing, component manufacture, and assembly • Recycling of vehicle components, time-sensitive hybrid of avoided burden and cut-off approach
Battery	• Production of the battery packs, including extracting and processing of raw materials, cell production, and pack assembly • *Not included*: second-life use and recycling
Maintenance	• In-service replacement of consumables, including tires, exhaust/aftertreatment, coolant, oil, urea, and others

47 Bieker, *A Global Comparison*.

48 International Energy Agency, *Global EV Outlook 2024: Trends in Electric Vehicle Batteries* (April 2024), https://www.iea.org/reports/global-ev-outlook-2024/trends-in-electric-vehicle-batteries.

49 Eyal Li, Georg Bieker, and Arijit Sen, *Electrifying Road Transport with Less Mining: A Global and Regional Battery Material Outlook* (International Council on Clean Transportation, 2024), https://theicct.org/publication/ev-battery-materials-demand-supply-dec24/.

Table A2. Vehicle manufacturing, battery manufacturing, and maintenance emissions for BEV passenger cars in Europe by vehicle segment

Year	Vehicle type	Passenger car glider and powertrain manufacturing emissions (t CO_2e/t vehicle)	Vehicle weight (no battery, kg)	Vehicle manufacture (g CO_2e/km)	Maintenance (g CO_2e/km)	Distance travelled (km in 18 years, the average lifetime of a car)	Carbon intensity of average battery used (kg CO_2e/kWh)	Battery capacity (kWh)	Battery manufacture LCA GHG emissions (g CO_2e/km)	GHG emissions for BEV (g CO_2e/km)
2021	Small car	4.7	1,155	27	5	198,000	70	45	15.91	47.91
	Medium car	4.7	1,382	27	5	243,000	70	45	12.96	44.96
	Large car	4.7	1,537	27	5	270,000	70	70	18.15	50.15
2030	Small car	4.0	1,155	23	4	198,000	53	54	14.45	41.45
	Medium car	4.0	1,382	23	4	243,000	53	54	11.78	38.78
	Large car	4.0	1,537	23	4	270,000	53	84	16.49	43.49

Table A3. Vehicle manufacturing, battery manufacturing, and maintenance emissions for ICEV passenger cars in Europe by vehicle segment

Year	Vehicle type	Passenger car glider and powertrain manufacturing emissions (t CO_2e/t vehicle)	Vehicle weight (kg)	Vehicle manufacture (g CO_2e/km)	Maintenance (g CO_2e/km)		Distance traveled (km in 18 years, the average lifetime of a car)	GHG emissions for ICEV (g CO_2e/km)	
					Gasoline/ LPG/CNG	Diesel		Gasoline/ LPG/CNG	Diesel
2021	Small car	5.2	1,155	30	5	7	198,000	35	37
	Medium car	5.2	1,382	30	5	7	243,000	35	37
	Large car	5.2	1,537	30	5	7	270,000	35	37
2030	Small car	4.4	1,155	26	5	7	198,000	31	33
	Medium car	4.4	1,382	25	5	7	243,000	30	32
	Large car	4.4	1,537	25	5	7	270,000	30	32

For LCVs, the battery manufacture and maintenance emission values correspond to those of a large-segment passenger car. However, in calculating vehicle manufacturing emissions, the following vehicle weights are used to correspond with the ranges allowed for the different classes of N1 LCVs: 1,200 kg for Class I, 1,500 kg for Class II, and 1,900 kg for Class III.

HEAVY-DUTY TRUCKS AND BUSES

Table A3 depicts the GHG emissions from vehicle manufacture, maintenance, and battery manufacture for BEV HDVs, including two different HDT segments and urban buses. These values are based on an ICCT LCA that focused on European HDVs.[50] HDV manufacturing emissions are calculated similarly to those of passenger cars and LCVs but are based on manufacturing emissions of 6.6 t CO_2e/t vehicle in 2021 and 5.6 t CO_2e/t vehicle in 2030, reflecting the lower-carbon energy inputs required for the manufacture of HDVs. It is assumed that the average weight of HDTs will exhibit a slight decline from 2021 to 2030. The table outlines vehicle manufacture emissions for 12-ton and 40-ton HDTs only. For HDT segments that weigh between 12 and 40 tons, vehicle manufacturing emissions are derived using linear interpolation.

Battery manufacture GHG emissions are calculated using the same method described in the passenger car and LCV section. Both the battery capacity and the average battery's carbon intensity are assumed to be lower in 2030 due to cleaner electric grids and the assumption that BEV batteries will produce more power per kilogram as battery costs decrease and battery densities increase. We assume one battery replacement during the life of the BEV HDV based on a review of estimated battery lifetimes.

Maintenance emissions by fuel type are consistent with those outlined in the passenger car and LCV section.

50 O'Connell et al., *A Comparison.*

Table A4. Vehicle manufacturing, battery manufacturing, and maintenance emissions for battery electric heavy-duty vehicles in Europe by type

Year	Vehicle type	HDV glider and powertrain manufacturing emissions ($t\ CO_2e/t$ vehicle)	Vehicle unladen weight (kg)	Vehicle manufacture ($g\ CO_2e/km$)	Maintenance ($g\ CO_2e/km$)	Distance traveled (km in 20 years, the average lifetime of an HDV)	Carbon intensity of average battery used ($kg\ CO_2e/kWh$)	Battery capacity (kWh)	Battery manufacture LCA GHG emissions ($g\ CO_2e/km$)	Battery manufacture LCA GHG emissions ($g\ CO_2e/km$) for HDVs with two batteries	GHG emissions for BEV ($g\ CO_2e/km$)
2021	12 t truck	6.6	4,176	32.20	5	856,000	58	300	20.33	40.65	77.85
	40 t tractor-trailer	6.6	14,844	78.82	5	1,243,000	58	900	42.00	83.99	167.81
	Urban bus	6.6	11,600	86.90	5	881,000	58	300	19.75	39.50	131.40
2030	12 t truck	5.6	3,800	24.86	4	856,000	37	250	10.81	21.61	50.47
	40 t tractor-trailer	5.6	13,084	58.95	4	1,243,000	37	700	20.84	41.67	104.62
	Urban bus	5.6	11,600	73.73	4	881,000	37	250	10.50	21.00	98.73

L-CATEGORY

Table A4 depicts the GHG emissions from vehicle manufacture, maintenance, and battery manufacture for L-category BEVs and gasoline ICEVs. Vehicle production and recycling emissions for the glider and powertrain are derived from vehicle-mass-dependent factors from an LCA study on motorcycles in Barcelona.[51] Production emissions are assumed to be 15% lower in 2030 compared with 2021.

Battery manufacture GHG emissions are calculated using the same method described in the passenger car and LCV section. Similarly, the battery capacity is assumed to increase by 20% and the average battery's carbon intensity is assumed to decrease by 20% in 2030.

Maintenance emissions are slightly higher for gasoline ICEVs as combustion engine vehicles generally require more maintenance than electric vehicles. The emissions factors specific to powertrain and vehicle weight are scaled with the weight of the considered vehicle models.[52]

Table A5. Vehicle manufacturing, battery manufacturing, and maintenance emissions for battery electric and gasoline L-Category vehicles

Year	Vehicle type	Model	Vehicle production and recycling ($t\ CO_2e$)	Vehicle production and recycling ($g\ CO_2e/km$)	Maintenance ($g\ CO_2e/km$)	Distance travelled (km in 12 years, the average lifetime of a scooter)	Carbon intensity of average battery used ($kg\ CO_2e/kWh$)	Battery capacity (kWh)	Battery manufacture LCA GHG emissions ($g\ CO_2e/km$)	GHG emissions for BEV ($g\ CO_2e/km$)
2023	Scooter	Honda BEAT gasoline ICEV	0.3	3.01	1.9	99,600				4.91
		Gesits G1 BEV	0.4	4.02	1.0	99,600	56	1.4	0.79	5.90
2030	Scooter	Honda BEAT gasoline ICEV	0.255	2.56	1.9	99,600				4.46
		Gesits G1 BEV	0.34	3.14	1.0	99,600	44.8	1.7	0.76	5.18

51 Gerson Carranza et al., "Life Cycle Assessment and Economic Analysis of the Electric Motorcycle in the City of Barcelona and the Impact on Air Pollution," *Science of The Total Environment* 821 (May 2022): https://doi.org/10.1016/j.scitotenv.2022.153419.

52 Mera and Bieker, *Comparison of the Life-Cycle Greenhouse Gas Emissions.*

APPENDIX B: CARBON INTENSITY OF ELECTRICITY AND FUEL FEEDSTOCKS

CARBON INTENSITY OF BELGIUM'S ELECTRICITY GRID

Table B1 presents the assumed carbon intensity of Belgium's electricity grid from 2019 to 2029. For 2019–2021, the emission factors for national electricity consumption were derived using the Covenant of Mayors life-cycle approach, based on data from the European Commission's Joint Research Centre (JRC).[53]

Between 2022 and 2023, the yearly emission factors for Belgian electricity production were calculated by multiplying the share of each electricity generation technology, as estimated by Electricity Maps, with their respective life cycle GHG emissions based on median values in the Intergovernmental Panel on Climate Change's 2011 report.[54] A 5% transmission and distribution loss, as reported by the Council on European Energy Regulators (CEER) in 2020, was also factored into the calculations.[55]

For the years 2024 to 2040, emission factors were estimated using the JRC's Policy-Oriented Tool for Energy and Climate Change Impact Assessment (POTEnCIA)'s projections of net electricity generation by technology, along with the corresponding life cycle GHG emissions from the IPCC 2011 (median).[56] This projection took into account a recent decision to extend the operation of two nuclear reactors until 2035, with adjustments made to the net electricity generation values for nuclear plants from 2026 to 2035. Additionally, a 5% transmission and distribution loss was incorporated into these projections.[57]

CARBON INTENSITY OF BELGIUM FUEL FEEDSTOCKS

The gasoline blend in Belgium contains 10.7vol.% ethanol, primarily derived from feedstocks such as corn, wheat, and sugar beet. Table B2 presents the carbon intensity of ethanol and the composition of its feedstocks for 2020 and 2030. The values for feedstock shares, WTT, ILUC, and WTW are based on a 2021 ICCT LCA.[58] In compliance with the Renewable Energy Directive, it is anticipated that by 2030, the proportion of cellulosic ethanol, sourced from materials like wheat straw, will increase. For both 2020 and 2030, the carbon intensity of the Belgium ethanol mix per megajoule is lower than that of fossil gasoline. However, certain feedstocks, such as wheat and barley/rye, exhibit higher carbon intensity than fossil gasoline when accounting for ILUC.

Table B1. Carbon intensity of Belgium's electric grid by year

Year	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029
g CO_2e/kWh	230	237	208	163	157	135	140	219	214	214	214
Year	**2030**	**2031**	**2032**	**2033**	**2034**	**2035**	**2036**	**2037**	**2038**	**2039**	**2040**
g CO_2e/kWh	211	215	215	213	215	213	297	260	228	198	203

53 Joana Bastos, Fabio Monforti-Ferrario, and Giulia Melica, *Covenant of Mayors for Climate and Energy: Greenhouse Gas Emission Factors for Local Emission Inventories* (Publications Office of the European Union, 2024): https://doi.org/10.2760/014585.

54 "Live 24/7 CO_2 Emissions of Electricity Consumption," Electricitymaps.com, accessed November 13, 2024, https://app.electricitymaps.com/zone/BE/; William Moomaw et al., "Annex II: Methodology," in *Renewable Energy Sources and Climate Change Mitigation*, ed. Ottmar Edenhofer et al. (Intergovernmental Panel on Climate Change, 2011), https://www.ipcc.ch/report/renewable-energy-sources-and-climate-change-mitigation/.

55 Council of European Energy Regulators, *2nd CEER Report on Power Losses* (March 23, 2020), https://www.ceer.eu/wp-content/uploads/2024/04/C19-EQS-101-03_Report_on_Power_Losses_3.pdf.

56 Leonidas Mantzos et al., *POTEnCIA Central-2018 Scenario* (European Commission, Joint Research Centre, 2019), http://data.europa.eu/89h/3182c195-a1fc-46cf-8e7d-44063d9483d8.

57 ENGIE, "ENGIE Signs a Final Agreement."

58 Bieker, *A Global Comparison*.

Table B2. Share, WTT (excluding ILUC), ILUC, and total WTW GHG emissions of different feedstocks used in the 2020 and 2030 Belgian ethanol mix compared with fossil gasoline

Feedstock	Share in ethanol mix (vol.%)		WTT, excluding ILUC ($g\ CO_2e/MJ$)		ILUC ($g\ CO_2e/MJ$)		WTW, including ILUC ($g\ CO_2e/MJ$)	
	2020	2030	2020	2030	2020	2030	2020	2030
Corn	38	34	57	57	14	14	71	71
Wheat	30	26	63	52	34	34	97	86
Sugar beet	21	21	28	28	15	15	43	43
Barley/rye	7	6	65	65	38	38	103	103
Wheat straw	4	13	18	18			18	18
EU ethanol mix							73	63
Fossil gasoline							93	93

The average diesel blend in Belgium comprises 10.7vol.% biogenic diesel, with 64vol.% being fatty acid aethyl ester (FAME) biodiesel and 36vol.% being hydrotreated vegetable oil (HVO). The feedstock composition and carbon intensity for FAME and HVO are detailed in Table B3 and Table B4, respectively, and are predominantly sourced from the 2021 ICCT LCA.[59] The primary feedstocks for both FAME and HVO include rapeseed oil, palm oil, soybean oil, and used cooking oil. For biodiesel derived from food crops like rapeseed oil, palm oil, soybean oil, or sunflower oil, the direct GHG emissions during production and the associated ILUC emissions are notably higher than the production and combustion emissions from fossil diesel. Notably, Belgium aligned with Denmark, France, and the Netherlands in banning the least sustainable oils, palm and soybean, for fuel use in 2022 and 2023.[60] This led to a 28% reduction in WTW emissions for FAME and a 46% reduction for HVO in 2023 compared with 2019. Advanced biofuels, such as those derived from residues and wastes like used cooking oil, offer a significant GHG reduction compared with fossil diesel, especially as they do not contribute to ILUC.

Table B3. Share, WTT (excluding ILUC), ILUC, and total WTW GHG emissions of different feedstocks used in the 2019, 2022, 2023, and 2030 Belgian FAME mix compared with fossil diesel

Feedstock	Share in biodiesel mix (vol.%)				WTT, excluding ILUC ($g\ CO_2e/MJ$)				ILUC ($g\ CO_2e/MJ$)				WTW, including ILUC ($g\ CO_2e/MJ$)			
	2019	2022	2023	2030	2019	2022	2023	2030	2019	2022	2023	2030	2019	2022	2023	2030
Rapeseed oil	52	72	77	70	51	51	51	51	65	65	65	65	116	116	116	116
Palm oil	20				36				231				267			
Soybean oil	5	5			58	85			150	150			208	208		
Sunflower oil	1	1	1	8	42	42	42	42	63	63	63	63	105	105	105	105
Used cooking oil	17	17	17	15	8	8	8	8					8	8	8	8
Animal fats	5	5	5	5	14	14	14	14					14	14	14	14
Other residual				2				8								8
Total FAME													127	97	92	92
Fossil diesel													95	95	95	95

59 Bieker, *A Global Comparison.*

60 Rhett Butler, "Belgium Bans Biofuels Made from Palm Oil, Soy," *Mongabay Environmental News*, April 13, 2021, https://news.mongabay.com/2021/04/belgium-bans-biofuels-made-from-palm-oil-soy/.

Table B4. Share, WTT (excluding ILUC), ILUC, and total WTW GHG emissions of different feedstocks used in the 2019, 2022, 2023, and 2030 Belgian HVO mix compared with fossil diesel

	Share in HVO mix (vol.%)				WTT, excluding ILUC ($g\ CO_2e/MJ$)				ILUC ($g\ CO_2e/MJ$)				WTW, including ILUC ($g\ CO_2e/MJ$)			
Feedstock	**2019**	**2022**	**2023**	**2030**	**2019**	**2022**	**2023**	**2030**	**2019**	**2022**	**2023**	**2030**	**2019**	**2022**	**2023**	**2030**
Rapeseed oil	18	63	65	59	52	52	52	52	65	65	65	65	117	117	117	117
Palm oil	45				35				231				266			
Soybean oil	2	2			60	60			150	150			210	210		
Sunflower oil	0.4	0.4	0.4	0.4	42	42	42	42	63	63	63	63	105	105	105	105
Used cooking oil	24	24	24	24	11	11	11	11					11	11	11	11
Animal fats	11	11	11	11	16	16	16	16					16	16	16	16
Other residual				6				11.1								11
Total HVO													150	83	81	75
Fossil diesel													95	95	95	95

APPENDIX C: AVERAGE VEHICLE ELECTRICITY AND FUEL CONSUMPTION

Table C1 presents the average fuel and/or electricity consumption of ICEVs, HEVs, BEVs, and PHEVs. Since only emissions were reported for ICEVs, we calculated the average fuel consumption first by determining an activity-weighted average of tailpipe emissions in grams of CO_2 per 100 kilometers across all segments and vehicle emission standards. Subsequently, the average CO_2 per unit of fuel mass was used to calculate kilograms of fuel, and fuel density was applied to determine liters per 100 km. The fuel consumption is estimated for urban conditions representative of Brussels's average vehicle speed and trip lengths. Compared with type-approval fuel consumption, urban fuel consumption per 100 km tends to be significantly higher due to a higher contribution of cold starts and idling, as well as the lower engine efficiency at low speed.

Electricity consumption in passenger cars is reported in kilowatt-hours. To derive a kWh per 100-kilometer estimate, this figure was divided by the total activity. For non-passenger car vehicles, an estimation of electricity consumption was determined using a factor that compares fuel consumption to electricity consumption. This factor was sourced either from the literature or directly from the passenger car data, comparing gasoline and diesel cars with their electric counterparts. A weighted average across all segments and vehicle emission standards was then applied to get a category-level metric. The electricity estimate aims to reflect real-world consumption, including charging losses of 19%.

Table C1. Average vehicle electricity and fuel consumption by vehicle, fuel, and powertrain types

Fuel (kg or L) and electricity consumption (kWh) per 100 km	Bus	Heavy-duty truck	Light commercial vehicle	Passenger car	L-Category
Gasoline ICEV			14.8 L	12.7 L	5.6 L
Gasoline HEV				7.0 L	
Diesel ICEV	50.4 L	42.3 L	12.3 L	9.1 L	4.1 L
CNG ICEV	44.4 kg			9.0 kg	
LPG ICEV				7.3 kg	
BEV	147.5 kWh	116.9 kWh	25.2 kWh	20.6 kWh	7.5 kWh
Gasoline PHEV				7.4 L + 4.7 kWh	

APPENDIX D: SENSITIVITY ANALYSIS

The sensitivity analysis uses remote-sensing data collected from vehicles in the Brussels Capitol Region in 2020. The mean g CO_2/km was derived for each combination of vehicle segment and fuel type using Worldwide Harmonised Light vehicles Test Procedure (WLTP) type-certified CO_2 levels. Two adjustments were made to the WLTP type-certified values to reflect real-world urban conditions. First, g CO_2/km values were adjusted for real-world fuel consumption. Secondly, values were adjusted to reflect urban driving conditions using findings from a study that found emissions under urban driving conditions are approximately 10% higher for all segments and fuel types.[61]

Using the mean real-world g CO_2/km under urban driving conditions, we derived average distance-specific TTW and WTT GHG emissions by fuel type and vehicle segment. The fuel category composition (e.g., fossil gasoline or bioethanol) of gasoline and diesel fuel, as modeled using COPERT, was assumed to be consistent across both datasets. The mean urban CO_2/km figures represent tailpipe emissions, including those from biofuels in the fuel mix. To calculate TTW emissions following the methodology used in the COPERT analysis, only tailpipe emissions from fossil fuels, selective catalytic reduction, and lubricants were considered, while biofuel-related emissions receive biocredits for CO_2 capture during production. The fuel category breakdown in COPERT informed the proportion of emissions attributed to each fuel source in the gasoline and diesel mixes. Finally, TTW emissions were scaled using a ratio of CO_2e (including CH_4, BC, N_2O, and CO_2) to CO_2 emissions to estimate total GHGs, yielding a ratio of 1.018.

To estimate WTT emissions, we used the shares of emissions from different fuels and applied the same WTT calculations described above. We assumed the same values for vehicle production and maintenance emissions from the COPERT analysis to derive total CO_2e/km per fuel type and vehicle segment. To calculate the total emissions, this number was multiplied by the annual vehicle activity for passenger cars of each respective fuel type and segment in each of the scenarios. We kept the vehicle emissions for battery electric, hybrid, and PHEVs the same as those modeled in COPERT.

61 Alex Stewart et al., *Quantifying the Impact of Real-World Driving on Total CO2 Emissions from UK Cars and Vans* (Element Energy and International Council for Clean Transportation, 2015), https://www.theccc.org.uk/publication/impact-of-real-world-driving-emissions/.

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