LEZ MODEL

ICCT LEZ model v2.1 documentation

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INTRODUCTION

The ICCT's LEZ model is a Python-based tool designed to assess the impact of low emission zone (LEZ) implementations on fleet emissions in cities. Fleet-average emission factors (EFs), in terms of g/km, can be evaluated for local pollutants such as particulate matter (PM) and nitrogen oxides (NOx), as well as greenhouse gases (GHG), both for Tank-to-Wheel (TTW) and Well-to-Wheel (WTW) emissions. The model includes a turnover module that projects future fleet evolution, incorporating varying powertrain shares for future sales and natural vehicle retirements. The LEZ model allows for the evaluation of impacts on the fleet and average EFs across different scenarios of LEZ implementation and vehicle owner response (section Consumer-response Modelling), enabling easy comparison of relative emission reductions due to LEZ policies.

The LEZ model was first developed in 2020 by Caleb Braun, Yoann Bernard, and Josh Miller to inform the TRUE publication "Impacts of the Paris low-emission zone and implications for other cities". Version 2.1 was developed in 2022-2023 by Jakob Schmidt, Rohit Nepali, Kaylin Lee, and Yoann Bernard.

SCOPE

The LEZ model calculates the fleet composition and resulting fleet-average emission factors (typically in g/km). The fleet composition is expressed as a share of total activity during the base year, measured in terms of Vehicle Kilometers Traveled (VKT). Fleet composition is defined by the distribution of fuels (gasoline, diesel, or BEV), vehicle age, and emission control standards. Depending on data availability, the calculations can be split into different vehicle categories, such as cars and vans. The model assumes that LEZ impacts are evaluated for the entire fleet, with bans and fleet evolution expressed as changes in shares of total activity. Accordingly, the model also calculates the relative activity growth compared to the base year activity. The resulting fleet-average emission factors can be multiplied with the base year activity to calculate a fleet-level emission inventory (EI). A typical data source that informs fleet composition and emission factors is remote sensing (RS) campaigns, which can provide vehicle counts, a proxy for vehicle activity, and measure real-world vehicle emission factors. In the absence of RS data, fleet composition can be derived from Automatic License Plate Recognition (ALPR) camera data, traffic count data, etc.

DEFINITIONS

This section provides definitions of key terms as they are used and implemented within the model.

1. **Fleet Composition**: The distribution of vehicles in a given area, defined by fuel type, age, and emission control standards.
2. **Base Year**: The reference year from which calculations or projections begin, used as a starting point for fleet composition, activity levels, and other model inputs. All future changes, such as fleet turnover or emissions, are calculated relative to the base year.

3. **Low Emission Zone (LEZ)**: An area where polluting vehicles are restricted or banned to reduce air pollution, based on criteria like vehicle age or emission control standard.
4. **Vehicle Kilometers Traveled (VKT)**: A measure of the combined distance traveled by vehicles within a specific area and time frame. VKT can represent the activity of individual vehicles, groups of vehicles, or categories such as fuel type, vehicle age, or emission standard, and is commonly used to assess vehicle activity.
5. **Local Pollutants**: Harmful emissions such as particulate matter (PM) and nitrogen oxides (NOx) that directly affect air quality in the vicinity where they are released. These pollutants are usually associated with vehicle exhaust and can have significant health and environmental impacts.
6. **Greenhouse Gases (GHG)**: Gases such as CO2, methane, and nitrous oxide that contribute to global warming, distinguished in the model by TTW (Tank-to-Wheel) and WTW (Well-to-Wheel) emissions. The user can provide inputs to express these emissions in terms of CO2 equivalents (CO2e) based on global warming potential (GWP).
7. **Emission Control Standard**: Regulatory limits that define the maximum allowed emissions from vehicles, such as Euro standards for NOx and PM emissions.
8. **Emission Factor (EF)**: A measure of the mass of pollutants emitted per distance traveled, usually expressed in grams per kilometer (g/km), used to quantify pollutants such as PM, NOx, and CO2. It is used to quantify both local pollutants and GHG emissions.
9. **Remote Sensing Campaigns**: Emission testing campaigns that measure real-world tailpipe emissions from vehicles using spectroscopy, often used to inform fleet composition and emission factor inputs.
10. **Turnover:** The process of replacing older vehicles with newer ones in a fleet through natural retirements and vehicle sales. In the LEZ model, natural turnover refers to the fleet evolution without considering LEZ restrictions. These restrictions are applied afterward to the "naturally turned over fleet".
11. **Ban Reaction**: The behavioral response of consumers or vehicle owners when their vehicles are restricted from entering an LEZ, influencing shifts in fleet composition.
12. **Age of a Vehicle**: The difference between the current year and the year the vehicle was registered. Vehicle age can be used to estimate emission control standards, predict retirements, and can serve as the basis for LEZ restrictions.

METHODOLOGY

The LEZ model calculates fleet composition and fleet-average emission factors by considering various key inputs. It starts by defining the fleet composition in terms of fuel type, vehicle age, and emission control standards, and assigns emission factors based on these characteristics. The model projects future fleet evolution by considering vehicle retirements, new vehicle sales, and changes in fuel composition. LEZ implementations are modeled by applying restrictions to certain vehicle categories, shifting activity to compliant vehicles or alternative transport modes. The final outputs include the fleet's emission inventory and the potential emission reductions achieved under different LEZ scenarios.

Fleet composition

The model calculates the fleet composition in shares of the total activity compared to the base year.

$$S_x = \frac{A_x}{A_{\text{total}}^{\text{base year}}}$$

Where:

- S_x is the share of total activity for category x. x could be the fuel type, age, emission standard, or a combination of these.
- A_x represents the activity (e.g., vehicle kilometers traveled) for category x.
- $A_{\text{total}}^{\text{base year}}$ represents the total activity of the fleet in the base year.

For the base year the model calculates the activity share by age and fuel type $S_{\text{age, fuel}}$, based on user inputs (the next section explains how emission control standards are used to further specify the vehicle shares). These inputs are vehicle's fuel share S_{fuel}, as well as age share, that can depend on the fuel type $S_{\text{age}}(\text{fuel})$. A typical source for these inputs can be traffic counts e.g., during a RS campaign.

$$S_{\text{age, fuel}} = S_{\text{fuel}} \cdot S_{\text{age}}(\text{fuel})$$

For future years the composition is determined by the natural turnover and LEZ restriction impacts, as described in the corresponding sections below.

Expressing the fleet compositions in terms of shares relative to the base year means that these shares can exceed 100% in future years, while it is always 100% in the base year.

Emission control standards

In the LEZ model, each vehicle is assigned an emission control standard based on its fuel type and age. The emission control standards are used to determine the EFs for local pollutants (see Emission Factors section) and can be used in the implementation of LEZ-related bans (see LEZ Implementations section).

Assignment of emission control standards to vehicles

Depending on the region and implemented policies, the assignment of emission standards is not always strictly based on the registration date, as certain standards and certifications may be available before becoming mandatory.
The user can specify a dedicated input for the assignment of emission control standards to vehicles. This input takes the form of a distribution of standards based on vehicles' model years (MY), which can be derived from the calendar year (CY) and the vehicles' ages, represented as $S_{\text{standard}}(\text{CY, age})$. For example, 50% of vehicles registered in 2014 may comply with "Euro

4," while the remaining 50% comply with "Euro 5." Such inputs can be derived from remote sensing campaign data. The resulting composition consists of shares categorized by age, fuel, and emission standard:

$$S^{\text{CY}}_{\text{age,fuel,standard}} = S^{\text{CY}}_{\text{age,fuel}} \cdot S_{\text{standard}}(\text{CY, age})$$

If such direct mapping from age to emission control standard is not available, the model creates two scenarios that reflect different assumptions on the exact registration date and on the choice between the available standards on that date. In the optimistic scenario, vehicles are registered at the end of the year and meet the highest available standard at the time of registration. In contrast, in the pessimistic scenario, vehicles are registered at the beginning of the year and comply with the minimum required standard at the time of registration. The registration year is derived from the vehicle's age. For illustration: In 2024, emission standard A is mandatory, while a stricter standard B becomes available in June 2024, though not yet mandatory. Vehicles with a model year (MY) 2024 may comply with either standard A or B, depending on their registration date. In the optimistic scenario, vehicles are assumed to be registered after June, complying with the stricter standard B. In the pessimistic scenario, they are assumed to be registered before June, adhering only to the mandatory standard A.

Natural fleet turnover

The LEZ model aims to project future emission factors (EFs) and assess the impacts of LEZs on these EFs. To achieve this, it projects the future composition of the fleet based on user inputs and the calculation steps outlined in this section. The model begins its fleet turnover calculations from the base year, where the age and fuel distributions are known. For each subsequent year, vehicle retirements are calculated based on age, and sales of vehicles of various fuel types are calculated based on total sales growth projections, which must be provided by the user. The turnover is expressed as relative shares of the base year's fleet activity.

Retirements

Vehicle retirements are based on their age and year-over-year survival curves provided by the user. The survival curves consist of probabilities for each vehicle age, which quantify the likelihood of a vehicle surviving into the next year, i.e., aging by one year.

$$\text{Surviving Shares}^{\text{CY}}_{\text{fuel, age}} = S^{\text{CY-1}}_{\text{fuel,age-1}} \cdot R_{\text{survival}}(\text{age-1})$$

Where:

- $\text{Surviving Shares}^{\text{CY}}_{\text{fuel, age}}$ is the share of vehicles of a specific age (age) in the current calendar year (CY), after accounting for vehicle retirements from the previous year to the current year (before adding new sales in the current year).
- $S^{\text{CY-1}}_{\text{fuel, age-1}}$ is the share of vehicles of age (age-1) in the previous calendar year (CY-1).
- $R_{\text{survival}}(\text{age-1})$ is the survival probability for vehicles of age (age-1), indicating the likelihood that a vehicle survives and remains in the fleet for the next year.

Sales

New Vehicle Sales

The number of sales (also expressed in terms of shares relative to the base year fleet) is calculated by the model based on the yearly compound annual growth rate (CAGR) of sales, provided by the user. Iteratively, the share of vehicles of age 0 from the previous year is assumed to represent the new sales of that previous year. This share is then multiplied by $(1 + \text{CAGR})$to obtain the sales of new vehicles in the current year. These vehicles are assigned an age of 0, while the age 0 vehicles from the previous year are now considered age 1.

$$\text{New Sales}^{\text{CY}} = S_{\text{age=0}}^{\text{CY-1}} \cdot (1 + \text{CAGR})$$

Where:

- $\text{New Sales}^{\text{CY}}$ represents newly sold vehicles (age 0) in the current calendar year (CY).
- $S_{\text{age=0}}^{\text{CY-1}}$: Share of newly sold vehicles (age 0) in the previous calendar year (CY-1).
- $(1 + \text{CAGR})$: Growth factor applied to new vehicle sales, based on the compound annual growth rate (CAGR).

Fuel Composition of New Vehicle Sales

The fuel of the newly sold vehicles is determined by an additional user input that includes fuel share projections $S_{\text{fuel}}^{\text{sales, CY}}$. The change in fuel composition of new vehicles, e.g. an increase of electric vehicle sales in future years can be modelled with this input.

$$\text{New Sales}_{\text{fuel}}^{\text{CY}} = \text{New Sales}^{\text{CY}} \cdot S_{\text{fuel}}^{\text{sales, CY}}$$

Where:

- $\text{New Sales}_{\text{fuel}}^{\text{CY}}$: New vehicle sales for a specific fuel type in the current calendar year (CY).
- $\text{New Sales}^{\text{CY}}$: New total vehicle sales in the current calendar year.
- $S_{\text{fuel}}^{\text{sales, CY}}$: The share within new vehicle sales that corresponds to the specific fuel type in the current calendar year.

Used Vehicle Sales

Used vehicles can also be considered. The corresponding inputs determining used vehicle sales are the used-to-new ratio and the average age λ of used vehicles. The share of used vehicles sold each year (and thus added to the fleet) is calculated by multiplying the share of used vehicles by the used-to-new ratio. The age of these vehicles is not 0, as it is for new vehicles. Instead, a Poisson distribution is used to represent the age distribution of the used sales, with the mean representing the average age of used vehicles.

$$\text{Used Sales}_{\text{age}}^{\text{CY}} = \text{New Sales}^{\text{CY}} \cdot \frac{U}{N} \cdot P(\text{age}, \lambda)$$

Where:

- $\text{Used Sales}_{\text{age}}^{\text{CY}}$: Share of used vehicles of a specific age in the current calendar year (CY).
- New Sales$^{\text{CY}}$: Number of new vehicle sales in the current year.
- $\frac{U}{N}$: Ratio of total used vehicle sales (all ages) to new vehicle sales.
- $P(\text{age}, \lambda)$: Poisson distribution with mean λ, representing the average age of the used vehicles.

Fuel Composition of Used Vehicle Sales

Used vehicles follow the same fuel distribution as the vehicles that are already in the fleet.

$$\text{Used Sales}_{\text{fuel, age}}^{\text{CY}} = \text{Used Sales}^{\text{CY}} \cdot S_{\text{fuel, age}}^{\text{fleet, CY}}$$

Where:

- $\text{Used Sales}_{\text{fuel, age}}^{\text{CY}}$: Share of used vehicles of a specific fuel type and age in the current calendar year (CY).
- $\text{Used Sales}^{\text{CY}}$: Total share of used vehicles in the current calendar year.
- $S_{\text{fuel, age}}^{\text{fleet, CY}}$: Share of vehicles of that specific fuel type and age in the entire fleet in the current calendar year.

Resulting yearly fleet composition

The resulting fleet in each calendar year (CY) consists of the new vehicle sales, which are of age 0:

$$S_{\text{fuel, age=0}}^{\text{CY}} = \text{New Sales}_{\text{fuel}}^{\text{CY}}$$

And the fleet from the previous year that survived into the current year, in addition to the used vehicle sales:

$$S_{\text{fuel, age>0}}^{\text{CY}} = Surviving\ Shares_{\text{fuel, age>0}}^{\text{CY}} + Used\ Sales_{\text{fuel, age>0}}^{\text{CY}}$$

Where:

- $S_{\text{fuel, age>0}}^{\text{CY}}$: Share of vehicles older than age 0 (i.e., used or surviving vehicles) for a specific fuel type in the current calendar year (CY).
- $Surviving\ Shares_{\text{fuel, age>0}}^{\text{CY}}$: Share of vehicles older than age 0 that have survived from the previous year, for a specific fuel type in the current calendar year.
- $Used\ Sales_{\text{fuel, age>0}}^{\text{CY}}$: Share of used vehicle sales (vehicles older than age 0) for a specific fuel type in the current calendar year.

Emission Factors

For emission factors, we distinguish between local pollutants and greenhouse gases (GHG). The scope of local pollutants covers only tailpipe emissions. For GHGs, the scope can be broader and include upstream emissions, such as CO2 emissions from energy production for electric vehicles. The model is also capable of capturing seasonal variations in EFs that result from temperature differences.

Local Pollutants

The emission factors for local pollutants $EF_{\text{standard}}^{\text{pollutant}}$ are linked to emission standards. Each vehicle within the same group, defined by fuel type and emission standard, emits the same mass of local pollutants (e.g., PM and NOx) per unit of distance traveled. The emission factors associated with a standard can be derived from real-world measurements, such as remote sensing campaigns, type approval values, or other sources.

Greenhouse Gases

The GHG emission factors (EFs) are based on the vehicle's model year (MY) and the current calendar year (CY). The model calculates these using two inputs: energy intensity (energy per distance), which depends on the vehicle's MY and fuel type, and emission intensity (mass per energy), which depends on the CY. This approach accounts for both tailpipe and upstream emissions, including those from electric vehicles (EVs), and can incorporate future changes in energy production. The two inputs are multiplied for each CY and MY to obtain the EF in mass per distance:

$$EF_{\text{MY, CY}}^{\text{GHG}} = \text{Energy Intensity}_{\text{MY}} \cdot \text{Emission Intensity}_{\text{CY}}$$

Where:

- $EF_{\text{MY, CY}}^{\text{GHG}}$ is the emission factor based on the model year (MY) and calendar year (CY).
- $\text{Energy Intensity}_{\text{MY}}$ depends on the model year of the vehicle.
- $\text{Emission Intensity}_{\text{CY}}$ depends on the calendar year.

The two datasets, energy intensity and emission intensity, can be derived from various sources, including remote sensing data and other relevant datasets

Fleet-average Emission Factors

The fleet-average emission factor represents the weighted average of emissions per distance traveled, across all vehicles in the fleet, accounting for their distribution by age, fuel type, and emission control standards.

For local pollutants:

$$\overline{EF}_{\text{CY}}^{\text{pollutant}} = \sum_{\text{age, fuel, standard}} S_{\text{age, fuel, standard}}^{\text{CY}} \cdot EF_{\text{standard}}^{\text{pollutant}}$$

For GHGs:

$$\overline{EF}_{\text{CY}}^{\text{GHG}} = \sum_{\text{age, fuel, MY}} S_{\text{age, fuel, MY}}^{\text{CY}} \cdot EF_{\text{MY, CY}}^{\text{GHG}}$$

These fleet-average emission factors can be used by the user to calculate emission inventories (mass emitted) by multiplying the emission factors (mass per distance) with the base year activity (measured in distance).

LEZ Implementations

Low emission zones (LEZs) in cities can restrict vehicles from entering certain areas based on emission standards or vehicle age. The LEZ model allows users to define these restrictions by specifying the implementation year and vehicle restrictions. An important assumption is that the overall vehicle activity is not reduced by the LEZ-related bans, but rather that the activity is shifted to compliant vehicles or alternative transport options. In other words, any ban on older vehicles (that would have traveled a certain amount of VKT) is treated as an equivalent increase in VKT by newer, compliant vehicles. The model also assumes that all vehicles comply to the LEZ restrictions.

Turnover is first applied to the fleet without considering the impact of LEZ implementations for all years (natural fleet turnover). Then, for a given year, the impact of LEZs is calculated by redistributing VKT according to the consumer-response scenarios (explained in the next section). This allows the comparison of fleet-average EFs across different scenarios to evaluate the potential impact of LEZs.

The following section explains how this shift to different vehicles and modes of transport is modeled.

Consumer-response Modelling

For each modeled LEZ implementation, the user can select from a list of consumer responses or ban reactions. These ban reactions define how the activity of banned vehicles is redistributed among the remaining compliant vehicle options. After a vehicle group is banned, various alternative vehicle options may still be allowed to enter the LEZ. The model determines which vehicle group this activity will be shifted to. The responses can range from the most optimistic scenario, where activity shifts to the cleanest vehicle option, to the most pessimistic, where consumers switch to the most polluting but still-compliant vehicle option. The user can choose from several ban reactions to simulate a range of realistic effects from vehicle bans.

The model provides the following consumer-response hypotheses, which can be used to simulate vehicle owners' reactions to vehicle bans. Each scenario describes how consumers replace the activity previously performed by a now-banned vehicle:

Scenario name	Description
buy_best	Buy vehicle of highest available standard within same fuel type.

buy_worst	Buy vehicle of lowest available standard within same fuel type.
buy_bev	Buy BEV, that contribute no TTW but still have some WTT emissions from electric generation.
buy_zev	Switch means of mobility to cycling, walking, and zero- and low-emission public transport that are assumed to emit no TTW and no WTT emissions.
buy_gasoline	Buy gasoline type vehicle of highest available standard.
Buy_diesel	Buy diesel type vehicle of highest available standard.
buy_worst_proportional	Buy vehicle of lowest available standard. The fuel composition of that vehicle corresponds to the fuel composition of the fleet during the year of LEZ implementation. This can result in major shifts of fuel shares (e.g. from banned diesel to gasoline) to relatively old vehicles, one should be careful to check that this behavior is intended.
buy_new	Buy vehicle of highest available standard. The fuel composition of that vehicle corresponds to the share of the respective sales during the year of LEZ implementation.
buy_used	Buy used vehicles (in the same manner as in the natural turnover). The fuel composition of that vehicle corresponds to the share of the fleet during the year of LEZ implementation. The age of the installed vehicles follows a poisson distribution around the average entry age of used vehicles limited by the oldest available standard.