Study on the Expansion of Biyiud's Sustainable Cities Indicator through New Subindicators

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Abstract– This Final Degree Project presents a methodological study aimed at expanding Biyiud's sustainable cities indicator (EcoRating Biyiud Cities). This tool has been created to evaluate, in real time, progress in urban sustainability subindicators over the past twelve months, along with citizen and business participation in those efforts. It currently assesses decarbonization based on the reduction of electricity consumption from the grid.
To expand its scope, this study proposes two new subindicators that could be integrated into its calculation process due to their scalability, interpretability, and the availability of regularly updated data: a sustainable mobility index and a municipal structure index.
A prototype is developed and tested using real data from all Spanish municipalities, demonstrating the potential to enhance transparency and decision-making in local sustainability efforts. The work contributes to aligning local action with national energy transition goals, reinforcing the role of cities as key actors in sustainable development.
Keywords– urban sustainability, environmental indicator, sustainable mobility, municipal structure, Biyiud

1 Introduction

1.1 Context and Justification of the Study

In today's context, where sustainability is at the core of urban and environmental policies, the Biyiud platform identified the opportunity to implement a sustainability indicator for municipalities [1], [2]. This indicator enables local governments to showcase their commitment to sustainability and helps inform decision-making based on public and objective data.

To ensure greater representativeness, it is essential to clearly define what is meant by an urban sustainability indicator, its components, and the relationships among them. An indicator is a quantitative measure used to evaluate, compare, and monitor a specific phenomenon. It is constructed from objective data and enables complex information to be transformed into an understandable and actionable value.

Biyiud has developed a city ranking based on an indicator that evaluates the electricity consumption of Spanish municipalities. This centralized platform offers energy consumption data from various economic sectors — residential, industrial, service, and others — via API. With this data, Biyiud can analyze energy use trends and compare the energy sustainability of cities, highlighting those with more efficient consumption [2].

Working on this indicator allows a review and potential expansion of its current design, with the future aim of developing a more complete indicator. The goal is to integrate additional variables so the results become more representative and useful for local decision-making. To do this, a clear framework of relevant sustainability components must be established.

Furthermore, Biyiud's urban sustainability ranking serves as a tool to understand the connection between local actions and national outcomes in the energy transition. As Marquez et al. (2019) state, "national energy sustainability largely depends on how cities manage their energy systems." Having comparable indicators at the municipal level allows this impact to be measured transparently and in alignment with national decarbonization goals.

1.2 Sustainable Development Goals (SDGs) and Relevance to the Project

The 2030 Agenda for Sustainable Development established by the United Nations includes 17 Sustainable Development Goals (SDGs) aimed at addressing major global challenges and promoting a more inclusive and environmentally responsible development model. This project is particularly

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aligned with two of those goals:

- **SDG 7:** "Ensure access to affordable, reliable, sustainable, and modern energy for all" [23].
- **SDG 11:** "Make cities and human settlements inclusive, safe, resilient, and sustainable" [22].

These goals are highly relevant to the purpose of this project. On one hand, SDG 7 [23] is addressed through Biyiud's current sustainability indicator [1], which relies on data about electricity consumption, local generation, and self-consumption at both the municipal and facility level. The indicator promotes the use of modern and renewable energy sources, which aligns with the goal of increasing access to clean energy.

On the other hand, both the existing indicator and the improvements proposed in this study support the vision of future cities — sustainable, transparent, and citizen-centered. The indicator also makes sustainability-related information more accessible and understandable for the general public, reinforcing citizen engagement and trust.

1.3 The Importance of Sustainability in Cities

Although they cover just over 2% of the Earth's surface, cities are responsible for approximately 78% of global energy consumption and 60% of greenhouse gas emissions [21]. This concentration of resource use and emissions makes urban areas key players in addressing the climate crisis specially in the national energy transition due to their consumption patterns, complexity, and innovation potential [27].

Cities can and have to play a key role on the change [24], to do so they must have tools that help identify weaknesses and guide evidence-based action. This project aims to provide one such tool: a sustainability indicator that is updated regularly and can be disaggregated into specific components. By enabling local administrations to detect areas for improvement, this indicator supports more informed and sustainable urban governance.

1.4 Objective of the Study

This project is conceived as a methodological analysis and prototyping exercise aimed at expanding the urban sustainability indicator of the Biyiud platform. Based on a critical review of the existing UESI and Biyiud models, and the analysis of available data sources, the project aims to develop and apply new complementary subindicators for all Spanish municipalities.

General Objective: To analyze and prototype the integration of urban energy sustainability subindicators proposed in the study *"Measuring urban energy sustainability and its application to two Spanish cities: Malaga and Barcelona"* [17] into the Biyiud "Conscious Cities Ranking" platform [1], with the aim of improving the representativeness and scalability of its current energy sustainability index, while maintaining monthly update capability and transparency toward citizens.

Specific Objectives:

- Review the current methodology used by Biyiud to calculate its energy sustainability indicator.
- Compare it with the UESI model applied to Barcelona and Málaga [17].
- Analyze which UESI subindicators are technically feasible to integrate into the platform based on data availability and resolution (daily or monthly) [26].
- Study the relationship between municipal electricity consumption, local energy generation, and the national energy mix to understand its impact on municipal carbon footprints [27].
- Propose a set of new subindicators or methodological adjustments to improve the precision of the sustainability index without compromising its scalability to other municipalities.
- Prototype the implementation of these new subindicators using data from the INE, validating their technical and methodological viability.
- Define strategies to ensure transparency, interpretability, and regular update of the proposed subindicators.

1.5 Scope of the Project

This project focuses on the analysis, improvement, and prototyping of an urban energy sustainability subindicator based on the UESI model [17], with the goal of making it applicable and scalable within the Biyiud "Conscious Cities Ranking" platform.

The project includes a detailed study of the UESI [17] and Biyiud indicators to understand their functioning and evaluate the feasibility of implementing improvements. A key step involves identifying available data sources for the more than 8,000 Spanish municipalities, which is essential for assessing the applicability of new subindicators in the Biyiud ranking system [2].

Finally, a functional prototype will be developed using real data from all spaniard municipalities. This prototype will incorporate the new methodological proposals to integrate additional urban sustainability-related variables.

It should be noted that this project does not aim to develop the final production version of the new subindicators within the Biyiud system [2], nor to scale it to all Spanish municipalities. However, the project is oriented toward enabling that possibility in the future.

2 State of the Art

The adoption of the Sustainable Development Goals (SDGs) [20] has increased the demand for tools capable of quantifying progress toward urban sustainability. In this context, the study of urban energy sustainability has become especially relevant due to the crucial role cities play in decarbonization strategies.

Several research efforts have addressed urban sustainability from different global perspectives. However, few have focused specifically on the energy dimension and the operationalization of measurable and scalable subindicators based on real-time data. This section analyzes existing indicators and subindicators and their limitations, with special attention to the Urban Energy Sustainability Index (UESI) [17] and the current Biyiud model [1].

2.1 Existing Indicators and Their Limitations

Two urban sustainability indicators are examined in this section due to their relevance to the present study. The Biyiud indicator is central to this work, as it is the basis of the methodology being tested and expanded. On the other hand, the Urban Energy Sustainability Index (UESI) is included as a reference model.

2.1.1 Analysis of the Urban Energy Sustainability Index (UESI)

The study developed by Marquez et al. (2019) proposes an index to measure the energy sustainability of cities, called the Urban Energy Sustainability Index (UESI). This index has been applied to the cities of Málaga and Barcelona and is built from a set of indicators grouped into three categories: basic, instrumental, and complementary.

Basic Indicators

- **Fossil Fuels (FF):** Measures the amount of final energy produced using fossil fuels, showing the level of decarbonization of cities based on this indicator's evolution.
- **Local Electricity Production Using Renewables (LEPR):** Quantifies the amount of electricity produced locally in the municipality. It is particularly relevant because the local production and consumption of electricity from renewable sources have a positive impact on energy sustainability.
- **Local Thermal Production Using Renewables (LTPR):** Measures the amount of thermal energy produced locally from renewable sources. It is usually included within LEPR.
- **Air Quality (AQ):** Constructed based on WHO air quality guidelines (2005). It considers four pollutants and their limits as established by European directives.

Instrumental Indicators

- **Percentage of Non-pollution Vehicles (PV):** Percentage of non-polluting vehicles out of the total vehicle fleet in the municipality.
- **Workers Not Traveling in Private Vehicle (WNTPV):** Measures the number of trips made using methods of transport other than private vehicles. Indicates whether municipalities are taking effective measures to reduce private car use.
- **Buildings with High Efficiency Rating (BHER):** Indicates the number of buildings constructed with high energy efficiency.
- **Urban Energy Sustainability Plans (UESP):** Quantifies the intentions and planned actions to improve urban energy sustainability.

Complementary Indicators

- **Municipal Solid Waste Recycling Rate (SWRR):** Provides a percentage of the amount of municipal solid waste that is recycled — i.e., how much is recycled instead of sent to landfills or used for energy recovery.
- **Renewables in External Electricity Production (REEP):** Measures the amount of renewable electricity produced outside the municipality. It is considered complementary, as the goal should be to maximize local production.
- **Energy Affordability (EA):** Quantifies the economic effort that families must make to pay for energy. Particularly relevant to SDG 7.
- **Electricity Supply Quality (ESQ):** Built from Spanish service quality indicators: TIEPI (duration of service interruptions per installed power) and NIEPI (number of interruptions per installed power).

To construct the UESI, all values are standardized between 0 and 100. This requires a series of calculations that normalize subindicator values outside this range.

Some indicators currently have low values but are expected to grow exponentially in the future. To maintain index stability, an adjusted variable "n" is added to each of them. The indicators with exponential behavior and their assigned "n" values are: PV (n = 0.25), LEPR (n = 0.5), BHER (n = 0.5).

Once all the data are collected and normalized, they are grouped into the three categories mentioned above. Then, a subjective weighting is applied to each group, according to the authors' judgment. The final weights are: Basic indicators (50%), Instrumental indicators (30%), Complementary indicators (20%).

Limitations of the Indicator Although it is a complex and forward-looking indicator, which means that the same methodology can be used to create a resilient index over time, the UESI has a fundamental limitation: data availability.

The data required to keep this indicator updated are difficult to obtain and may only be available for specific municipalities. As a result, the indicator is not easily scalable without adding inaccuracies to its calculation, since it would be necessary to extrapolate information from other data sources to generate the index for each municipality.

Moreover, due to this scalability issue, the time and economic effort required by a company to apply this index to all municipalities in Spain—or even to a single region—would be very high.

2.1.2 Analysis of the Indicator Created by Biyiud

The model proposed by Biyiud is a city EcoRating, comparing the sustainability level of a municipality with others across Spain. It is updated monthly with dynamic data [2].

Biyiud constructs its indicator through the aggregation and normalization of a set of EcoScores based on sustainability missions or objectives and the active participation of local stakeholders involved with the platform.

EcoScores EcoScores are scores accumulated by municipalities, obtained through their participation and performance in sustainability objectives referred to as "missions." These EcoScores are derived from two components: Results and Participation.

EcoScores – Results Result-based EcoScores assess the municipality's performance compared to the same month of the previous year, analyzing the change over time. Currently, Biyiud includes the following missions:

- **Energy decarbonization:** Measures the reduction in CO_2 emissions related to energy consumption.
- **Non-energy decarbonization:** Measures the reduction in emissions from other sources, such as goods and services.

EcoScores – Participation Participation-based EcoScores measure the level of involvement of local actors (individuals, businesses, or administrations) in the sustainability objectives of the result-based EcoScores. They are calculated as the average EcoRatings of these actors. EcoRatings stem from specific sustainable actions, such as purchasing sustainable products from certain stores or using electricity from renewable sources.

Base Sustainability Score (BSS-City) This is the cumulative sum of all EcoScores (Results and Participation). The value resets every month to zero, allowing each period to be assessed independently and preserving the dynamic nature of the indicator.

Base Score Ranking (BSR-City) The BSR-City (Equation 1) is the normalized statistical value of the BSS-City. It is scaled between 1 and 10, based on the minimum and maximum values among all cities, enabling comparative results across municipalities. In other words, it positions each municipality relative to others to contextualize performance within the national reality.

$$\text{BSR–City} = \frac{\text{BSS–City} - \text{BSS–City}_{\min}}{\text{BSS–City}_{\max} - \text{BSS–City}_{\min}} \cdot (10 - 1) + 1 \quad (1)$$

EcoScore Biyiud Cities (EBC) and GDP Adjustment for Balanced Representation The EBC calculation applies a correction factor based on the municipality's economic strength. It adjusts the score according to the city's weight relative to national GDP, ensuring a balanced representation among municipalities. This prevents wealthier cities from overshadowing the sustainability efforts of those with fewer resources.

This approach aligns with the principles of SDG 11, which promotes inclusive, safe, resilient, and sustainable cities and communities. Ensuring that municipalities with limited financial resources can meaningfully contribute to sustainability efforts is essential for equitable participation in the energy transition.

As highlighted by Villa-Arrieta, M et al. (2019), a country's sustainability strongly depends on the energy behavior of its cities. Similarly, Cano-Huerta et al. (2019) state that "urban population concentration causes cities to reflect the country's energy consumption and sustainability." This justifies the importance of urban indicators in national sustainability strategies.

2.1.3 Available Indicators for the Construction of a New set of Subindicators

This section reviews the indicators currently available that may contribute to building a new urban sustainability subindicators within the Biyiud platform. It draws from the methodological proposals of the UESI index [17] and Biyiud's current model [1], analyzing for each case the viability, quality, and relevance of the data to assess urban and energy sustainability.

To be included, a dataset must meet the following criteria:

- Real-time data sources are prioritized; if not possible, the most updated data within a reasonable timeframe are accepted depending on the variable's nature.
- Each data source must have a clear and direct relationship with urban sustainability to ensure the relevance of the constructed subindicators.
- Each incorporated data point must be justifiable and contribute measurable value to assess local sustainability efforts and outcomes.

Basic Indicators

- **Fossil Fuels (FF):** FF refers to the amount of fossil fuels used to generate the electricity demanded by each municipality from the national energy mix. It is an extrapolation of the percentage of electricity from fossil or non-renewable sources. This data is obtained from the Red Eléctrica de España (REE) API [26] and can be calculated using weighted averages. The API provides real-time data by Autonomous Communities (CCAA) and offers various types of data, making it fully suitable for constructing this new subindicator.
- **Local Electricity Production Using Renewables (LEPU):** LEPU measures the proportion of electricity generated locally using renewable sources. Data are available at the provincial level for Biyiud through private accords. Although not in real time or at the municipal scale, these data offer a useful approximation to estimate local renewable capacity. It is a partially viable indicator, especially if complemented with information on installed capacity by postal code or province. It is particularly relevant, as highlighted in studies linking energy sustainability to Smart Cities.
- **Local Thermal Production Using Renewables (LTPR):** LTPR refers to thermal energy production (heating, hot water, etc.) using renewable sources

(biomass, solar thermal, geothermal). No updated or systematized sources have been found to provide this data at the municipal level. Therefore, this indicator is currently not viable. Further research into possible regional or municipal energy census sources is required.

- **Air Quality (AQ):** AQ data measure air quality through values of atmospheric pollution (NO_2, PM2.5, O_3, etc.). While there is no unified API, several public platforms (ICA MITECO, Generalitat, PurpleAir [18, 25, 13]) provide open and hourly updated data. Additionally, regulations mandate that this information be publicly accessible, ensuring its continuity. This indicator is fully viable and can be integrated using sensor maps or control stations.

Instrumental Indicators

- **Percentage of Non-pollution Vehicles (PV):** PV measures the percentage of non-polluting vehicles (electric, plug-in hybrids, etc.) in a municipality's vehicle fleet. The most recent data are from 2024 and are available from the DGT's municipal vehicle registry [7], broken down by fuel type. Although not real-time, the data are updated often enough to be integrated periodically. A socio-economic dimension is considered to adjust the score based on the financial effort involved in vehicle renewal for households. This indicator is fully viable and also compatible with the construction of the Sustainable Mobility Index (SMI) developed in this project.

- **Workers Not Traveling in Private Vehicle (WNTPV):** WNTPV indicates the percentage of people commuting without using a private vehicle (on foot, by bike, public transport, etc.). The most recent available data from INE [16] is not outdated, and although they may offer a general estimate, they do not meet the granularity for a robust indicator. For now, it is not viable, although future studies using new sources or mobility surveys could be considered.

- **Buildings with High Efficiency Rating (BHER):** BHER measures the share of buildings with high energy ratings. Currently, no complete or public dataset has been found that provides this information at the municipal level. Additionally, many older buildings do not yet have an official rating. A specific methodology would be required, if sufficient data was accessible with municipal granularity. At present, this indicator is not directly applicable.

- **Urban Energy Sustainability Plans (UESP):** UESP refers to the existence of local plans promoting urban energy sustainability, such as SEAPs or SECAPs [5]. It is difficult to quantify automatically, as there is no common database or standardized classification. Applying this indicator would require specific document analysis for each municipality. It is currently not viable as an automated indicator.

Complementary Indicators

- **Municipal Solid Waste Recycling Rate (SWRR):** SWRR measures the percentage of municipal solid waste that is recycled. Reliable and standardized sources are still being sought to obtain this data at the municipal level. It is a useful indicator to complement the sustainability assessment, but currently, no data source has been found at a municipal scale, only regional [15]. It is potentially viable if the appropriate data sources are identified.

- **Renewables in External Electricity Production (REEP):** REEP refers to the share of renewable electricity generated outside the municipality but included in its consumption through the national energy mix. These data can be partially obtained from SDG-related statistics or from REE [23, 26]. Its application may follow the same logic used for FF (Fossil Fuels), acting as a positive counterpart. It may be viable with an analogous methodology.

- **Energy Affordability (EA):** EA analyzes the financial capacity of households to cover energy costs. The INE provides data on this issue [19, 12], although not in real time, but with a frequency that allows annual or biannual modeling. It is a relevant indicator to introduce a social and equity dimension to energy sustainability. It is viable with periodic updates.

- **Electricity Supply Quality (ESQ):** ESQ refers to the quality of electricity supply, such as the frequency and duration of outages. Although the data are not real time, official annual reports from the Ministry are available [19, 12]. It can be used as an indicator of infrastructure resilience and quality. It is viable with annual updates.

2.1.4 Complementary Data Sources for Constructing New Subindicators

Beyond the indicators proposed in the UESI model, which has served as a reference, this project uses alternative data sources to adapt or reinterpret UESI indicators according to the data available and the methodology and objectives of Biyiud's EBC.

- **Municipal Vehicle Registry (DGT):** Data provided by the DGT allow for a detailed record of the vehicle fleet at the municipal level [7], broken down by environmental label (0, ECO, C, B, and unlabelled). These data, updated annually or biannually, offer a solid and systematic source for analyzing the evolution of the vehicle fleet and its potential contribution to CO_2 emissions.

  This registry has been essential for constructing the Sustainable Mobility Index (SMI), which measures several aspects of municipal mobility sustainability and is inspired by the PV indicator of the UESI.

- **Corine Land Cover (CLC):** The Corine Land Cover (CLC) project provides cartographic data on land use and land cover at the European scale [3], with periodic updates (every 6 to 8 years). These data are particularly useful for assessing urban compactness, the distribution of green areas, and the territorial morphology at the municipal level.

In this project, CLC data were used as the basis for constructing the Municipal Structure Index (MSI), an indicator designed to evaluate urban density and the availability of green space—key aspects of urban sustainability and citizens' quality of life.

Although some UESI model indicators are viable for integration into the Biyiud platform, other important dimensions of urban sustainability—such as sustainable mobility and urban structure—cannot be adequately represented using currently available municipal-level data.

For this reason, this study proposes the construction of new, custom subindicators that complement the existing ones and expand the system's analytical capacity. This methodological proposal is developed in detail in the next section.

Table 1: SUMMARY OF INDICATORS AND THEIR CHARACTERISTICS

Indicator	Avail.	Valid.	Appl.	Real-time	Biyiud	Scale
FF	X	X	X	X	X	Municipal
LEPU		X		X		Regional
LTPR		X	X			ND
AQ	X	X	X	X		Variable
PV	X	X	X			Municipal
WNTPV	X	X	X			National
BHER						ND
UESP		X	X			ND
SWRR	X		X			Regional
REEP	X	X	X	X	X	Municipal
EA		X	X			Regional
ESQ	X	X	X			Regional
DGT	X	X	X			Municipal
CLC	X	X	X			Municipal

Source: Author's synthesis based on data from INE, MITECO, REE, DGT and other official sources mentioned above.

3 METHODOLOGY

Although some UESI model [17] indicators are viable for integration into the Biyiud platform [1], other key dimensions of urban sustainability require the development of custom subindicators, adapted to the actual data available. For this reason, this chapter presents the methodology applied to build two new subindicators: the **Sustainable Mobility Index (SMI)** and the **Municipal Structure Index (MSI)**.

3.1 Sustainable Mobility Index (SMI)

The SMI aims to synthetically and comparably assess how the mobility model of a municipality supports or hinders environmental sustainability. To do so, three key dimensions are considered: emissions associated with the vehicle fleet, intensity relative to population, and the percentage of low-emission vehicles (ECO or 0 label). This subindicator is designed to be scalable nationwide and integrable within the Biyiud platform.

Emissions by Environmental Label Vehicle fleet data per municipality, broken down by environmental label (0, ECO, C, B, and no label) [8, 9, 10, 6], are available from the Spanish Directorate-General for Traffic (DGT) [11]. Each label is assigned an average annual CO_2 emission value based on EURO environmental standards [4] and vehicle type (electric, hydrogen, etc.). The values used are:

Table 2: AVERAGE EMISSIONS BY ENVIRONMENTAL LABEL

Label	Vehicle Type	Avg. Emissions (gCO_2/year)
0 [6]	Electric / Hydrogen	0
ECO [10]	Plug-in hybrids, natural gas, LPG	750
C [9]	Euro 4–6 petrol, Euro 6 diesel	1500
B [8]	Euro 3 petrol, Euro 4–5 diesel	1800
No label	Pre-Euro 3 vehicles	2100

Source: Author's elaboration based on DGT data and EURO emissions standards.

These data are combined with the 2024 municipal census to obtain figures such as vehicles per capita.

Intermediate calculations include:

- Total vehicle fleet emissions
- Average emissions per vehicle
- Percentage of low-emission vehicles
- Vehicles per capita

The **SMI** is built from a weighted combination of these three variables in Equation 2:

- 60%: Average emissions per vehicle (lower is better)
- 25%: Vehicles per capita (lower is better)
- 15%: Percentage of low-emission vehicles (higher is better)

$$\mathrm{IMS} = \left(1 - \frac{\mathrm{EM}}{\mathrm{EM}_{\max}}\right)\cdot 0.6 + \left(1 - \frac{\mathrm{VH}}{\mathrm{VH}_{\max}}\right)\cdot 0.25 + \left(\frac{\mathrm{PVN}}{\mathrm{PVN}_{\max}}\right)\cdot 0.15 \quad (2)$$

Integration into the Biyiud indicator To integrate this subindicator into the Biyiud sustainability scoring system [2], a linear normalization is applied based on the minimum and maximum values observed in the sample of analyzed municipalities. This procedure produces a final score between 1 and 10, as done with other subindicators on the platform. Calculated through Equation 3:

$$\mathrm{SMI}_{\mathrm{norm}_i} = \frac{SMI_i - SMI_{\min}}{SMI_{\max} - SMI_{\min}} \cdot (10 - 1) + 1 \quad (3)$$

3.1.1 Expected Results for the SMI

For municipalities with a modern vehicle fleet and a high proportion of electric and hybrid vehicles, positive results are expected. The SMI also includes a component that penalizes high vehicle density per capita. Municipalities with well-developed public transport networks—such as medium-sized cities or those with strong active mobility policies—are likely to achieve better scores.

In contrast, municipalities with a dispersed urban model, such as suburban residential areas or peripheral urbanizations, will tend to show lower values.

3.2 Municipal Structure Index: Relationship Between Green Areas and Urbanized Areas

The objective of this subindicator is to evaluate to what extent a municipality promotes a compact and sustainable urban model, avoiding dispersion and dependence on private vehicles, while also ensuring access to green and open spaces for its population. To do so, the subindicator measures population density over urbanized land and weights it with the quantity of green areas in the municipality. The result is expressed as a quantitative value and a qualitative classification.

Data sources and spatial processing The data used for this subindicator were obtained from different sources and required distinct processing steps. Land use classification was based on the 2018 Corine Land Cover (CLC) vector dataset [3]. Administrative municipal boundaries were also taken as vector layers, and the population register for 2024 was provided by the Spanish National Institute of Statistics (INE) [14].

Spatial processing was performed using GIS software (ArcGIS Pro), where municipal areas were classified according to CLC codes. Surfaces were grouped into urbanized areas, infrastructure, green zones (both urban and rural), and contaminating zones (e.g., mines and landfills). The data were exported to a spreadsheet where they were joined with population data, and the subindicator calculation methodology was implemented.

Land use classification Land use categories were grouped into the following functional categories, as detailed in Table 3. Contaminating zones were not included in the calculation for now, but may be penalized in future actualizations of the subindicator.

Table 3: SUMMARY OF MSI COMPONENTS

(A) LAND USE CLASSIFICATION

Functional Category	CLC Codes	Role in the Indicator
Urban Areas	111, 112, 121, 123, 133	Base for population density
Urban Green Areas	141	Positive complementary indicator
Rural Green/Open Areas	211–512	Soft positive indicator
Contaminating Areas	131, 132, 134	Future penalty in the indicator
Infrastructure	122, 124, 142	Not included

Source: Author's elaboration based on CLC data.

(B) MSI QUALITATIVE CATEGORIES

MSI Score	Classification
≥ 9	Very compact and green
≥ 6	Balanced compact
≥ 4	Semi-dispersed balanced
≥ 2.5	Rural or dispersed urbanization
< 2.5	Rural or highly dispersed

Source: Author's elaboration.

Subindicator construction The subindicator is calculated based on two basic variables:

- **Effective Urban Density (EUD)**: Measures how many people live per km² of urbanized land. Calculated through Equation 4

$$\text{EUD}_i = \frac{\text{Population}_i}{\text{Corrected Urban Area}_i} \tag{4}$$

In municipalities where no urban surface was detected (value 0 according to CLC), a corrective formula was applied to estimate the urban area as the greater of 0.5% of the total municipal surface or 0.2 km². This adjustment prevents distortions in urban density and ensures the subindicator can be applied even to small municipalities or those with no recorded urbanization in the available datasets in CLC.

- **Green-to-Urban Ratio (GUR)**: Quantifies the amount of green and open space per km² of urbanized land. Calculated through Equation 5.

$$\text{GUR}_i = \frac{\text{Green and Open Areas}_i}{\text{Corrected Urban Area}_i} \tag{5}$$

Both variables are first transformed using a logarithmic function to smooth out extreme values and then normalized to a 0 to 1 scale. The final subindicator (MSI) is computed as a weighted sum of the two normalized variables demostrated in Equation 6.

$$\text{MSI}_i = 0.7 \cdot \text{EUD}_{\text{norm}_i} + 0.3 \cdot \text{GUR}_{\text{norm}_i} \tag{6}$$

This formula integrates both calculated variables, giving more weight to urban compactness while also valuing the availability of green areas, which substantially improve quality of life and environmental health. The weighting helps moderate the disproportionate effect generated by rural municipalities with small urban areas and large surrounding green spaces. In this way, we prevent excessive green area from distorting the final result or penalizing compact municipalities with large amounts of unbuilt land.

Qualitative classification For better interpretation of results, MSI values are grouped into qualitative categories, as shown in Table 3.

Integration into the Biyiud indicator To enable comparison between municipalities and integration into the Biyiud scoring system [2], the index is normalized on a 1 to 10 scale using Equation 7.

$$\text{MSI}_{\text{norm}_i} = 1 + \left(\frac{\text{MSI}_i - \text{MSI}_{\min}}{\text{MSI}_{\max} - \text{MSI}_{\min}} \right) \cdot 9 \tag{7}$$

3.2.1 Expected Results for the MSI

Good results are expected for municipalities that combine high urban density—interpreted as efficient land use—with a solid provision of accessible and integrated green spaces.

These municipalities are likely to reduce dependence on private vehicles, offer better quality of life, and lower the economic and environmental footprint of urban development.

It is anticipated that dense, well-planned municipalities with notable green areas, such as Vitoria-Gasteiz or Pamplona, will perform better than municipalities with dispersed and inefficient structures, like Arroyomolinos.

Rural municipalities with large municipal areas, low density, and little or no CLC-detected urban area are expected to receive mid-range scores. This is due to a balance between compactness and natural environment, but without reaching the highest scores due to the limited population base.

4 Interpretation of Results

After applying the developed subindicators to all Spanish municipalities, trends and groupings emerge based on municipality types. These patterns allow us to assess the usefulness and discriminative capacity of the SMI and MSI.

To adapt the results interpretation to the space limitations of this paper, a representative sample of 17 Spanish municipalities was selected and can be seen in Table 7 for MSI and Table 8 for SMI. The sample was chosen using demographic, territorial, and urbanistic criteria to analyze how the SMI and MSI behave in different contexts and to identify strengths and limitations in their applicability.

4.1 Results interpretation for SMI

The SMI results seen in Table 8 and Figure 1 show consistently with the hypotheses proposed. In general, municipalities with lower vehicle density per capita and a fleet with lower average emissions tend to score higher on the index.

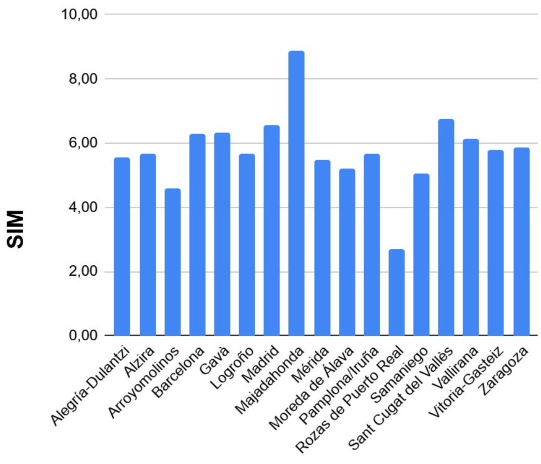

Fig. 1: SIM Scores Across Municipalities (Normalized Values).

Source: Author's elaboration based on computed SIM values.

As seen in Figure 1 Municipalities such as Barcelona and Sant Cugat del Vallès obtain scores around 6.5 out of 10, balancing high total emissions with low vehicle density and low emissions per vehicle. These cases illustrate how a robust public transport network helps reduce VH (vehicles per inhabitant) and consequently average emissions. Additionally, a significant share of sustainable vehicles supports their final scores.

In contrast, Arroyomolinos is an example of a municipality with a low proportion of clean vehicles, resulting in a poor performance with a score of 4.58 out of 10. The worst case scenario in terms of vehicles per capita is Rozas de Puerto Real, with 108.3. This town near Madrid has a lower registration tax for new vehicles and hosts businesses that offer vehicles for rent by the minute, taking advantage of this fiscal benefit. This significantly impacts the results for this municipality and others with similarly low vehicle registration taxes.

Overall, SMI results (Table 8) show a balanced distribution ranging between 2 and 9, with a concentration around 5 to 6, suggesting a certain degree of homogeneity in mobility patterns across many municipalities.

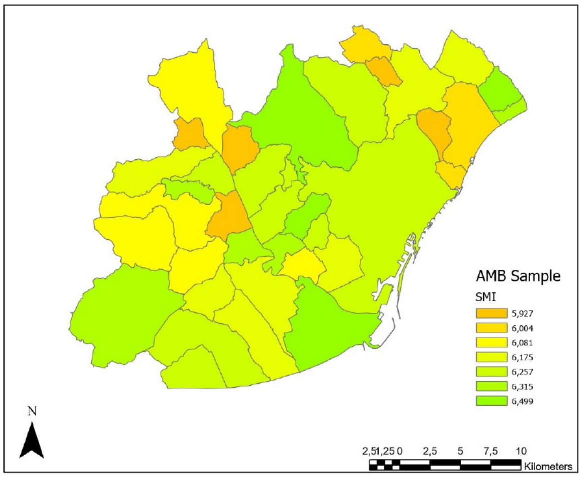

Fig. 2: SMI Results for a Sample of Municipalities in the AMB Region.

Source: Author's elaboration using public geospatial data from ICGC and AMB Open Data Portal. SMI calculated using Biyiud's methodology.

The results for the Sustainable Mobility Index (SMI) are generally positive across the AMB region, as shown in Figure 2. A key factor behind this performance is the widespread availability of public transport infrastructure, which reaches virtually all municipalities in the area. In addition, the population is highly accustomed to using public transport on a daily basis, further reinforcing sustainable mobility patterns.

However, the number of registered vehicles per inhabitant is close to one, which limits the overall sustainability of mobility in the region. This suggests that while public transport is accessible and widely used, private car mobility is still prevalent. On a more positive note, vehicle fleets in the AMB tend to be newer and emit less CO_2 compared to national averages, slightly mitigating their environmental impact.

4.2 Results interpretation for MSI

The core variable of the MSI—reflecting the ratio of green space to urban area per inhabitant—presents significant variability among municipalities.

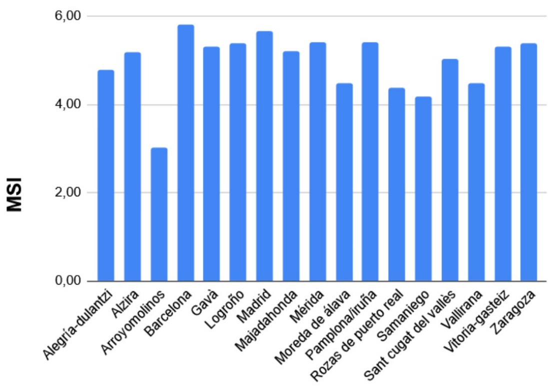

Fig. 3: MSI Results for a Sample of Municipalities in the AMB Region.

Source: Author's elaboration based on computed SIM values.

As seen in Table 7 and Figure 3Rural municipalities like Samaniego score very high, thanks to a green area per inhabitant well above the average. However, this green space is typically rural and not always directly accessible to residents.

Municipalities like Vallirana and Arroyomolinos, with large urban footprints and limited urban green space, are classified as "rural or dispersed urbanization." Even if they contain denser cores (e.g., Vallirana along the N-340), their low Effective Urban Density (EUD) penalizes their MSI score, accurately reflecting their morphology.

The results confirm that the logarithmic transformation is well applied and prevents major distortions in most cases.

However, very small municipalities show inaccuracies due to the limited sensitivity of CLC data. For example, Quart de les Valls (Valencia) is recorded as having only 0.001 km² of urban surface. Combined with a large amount of green/open space and a population of just over 1,000, it becomes the top-rated municipality by the MSI—even though it is not substantially different from others with similar characteristics.

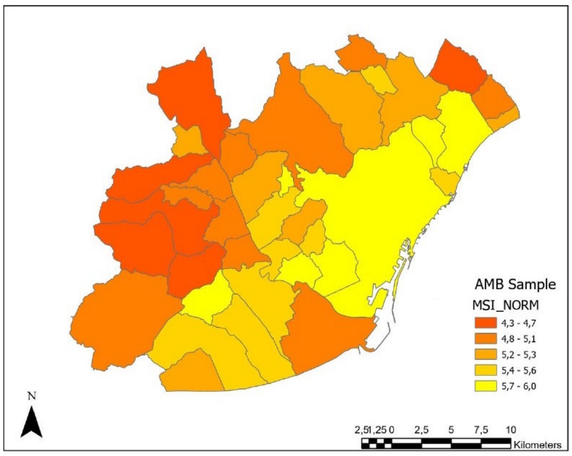

Fig. 4: MSI Results for a Sample of Municipalities in the AMB Region.

Source: Author's elaboration using public geospatial data from ICGC.

As seen in Figure 3 compact municipalities such as Barcelona, L'Hospitalet de Llobregat and Badalona score higher in the MSI compared to more dispersed municipalities like Castellbisbal or Vallirana. This difference is largely explained by the Effective Urban Density (EUD), which penalises municipalities with fragmented urban footprints and limited integration of green spaces. As shown in Figure 4, areas with higher density and more efficient land use tend to perform better in terms of structural sustainability.

4.3 Integration of the SMI and MSI into the Biyiud Platform

The two designed subindicators can be incorporated into the EBC as new missions within the category of EcoScores – Results. Their integration will consist of adding the normalized scores of the Sustainable Mobility Index (SMI) and the Municipal Structure Index (MSI), both on a 1 to 10 scale, to the current Base Sustainability Score (BSS-City), which until now only considered energy and non-energy decarbonization missions and participation-based scores.

For clarity and space reasons, the full updated formula for calculating the Base Sustainability Score for each municipality has been included in the Appendix (see Equation 8).

Although initially the SMI and MSI values are not expected to be displayed separately on the Biyiud platform, it is worth considering their individual presentation. Doing so would improve transparency and help the public understand the specific contribution of each dimension of urban sustainability to the overall score.

5 Conclusions

This project has explored the study and improvement of a sustainability indicator for Spanish municipalities within the EcoScore Biyiud Cities system. Based on the analysis of the UESI model and Biyiud's current methodology, a new methodological proposal was developed to enhance the ranking system with new subindicators relevant to urban sustainability.

The two subindicators created— Sustainable Mobility Index (SMI) and Municipal Structure Index (MSI)—provide a more complete view of two key dimensions of local sustainability: the impact of the mobility model and the municipality's urban structure, including the availability of green spaces.

The obtained results demonstrate that these subindicators have adequate discriminative power to characterize different types of municipalities and offer relevant information to guide local policies, especially those related to mobility and urban expansion.

Integrating these subindicators into EcoScore Biyiud Cities system will improve the ranking's ability to measure how local actions in mobility and municipal planning contribute to national decarbonization and sustainability goals.

The proposed methodology ensures that the SMI and MSI are scalable and replicable across all Spanish municipalities, and that they can be updated regularly as part of the EBC's dynamic system.

Looking ahead, the following recommendations are proposed:

- Consider the possibility of displaying the subindicators separately to enhance transparency and public understanding of how each factor contributes to the overall score.

- Assess and adjust the weight of these new subindicators within the EBC to ensure a balanced reflection of their real impact on urban sustainability, without distorting the current calculation.
- Study additional variables, such as accessibility to green space per inhabitant, industrial land, or polluting zones, to enrich the subindicator MSI in future iterations.

This work opens a pathway for improving and expanding the urban sustainability indicator within the Biyiud platform [1] and strengthens its potential to support the energy transition and the construction of more sustainable cities.

5.1 Limitations and Future Work

While the proposed subindicators offer a valuable enhancement to the current Biyiud methodology and provide useful insights for municipal sustainability assessment, several limitations have been identified throughout the development process. Addressing these limitations opens the door to future improvements and refinements in the subindicators design, data sources, and scope.

Sustainable Mobility Index (SMI) Despite its usefulness for comparative analysis, the Sustainable Mobility Index (SMI) presents some limitations. First, the indicator relies heavily on vehicle registration data, which may not fully capture real usage patterns or modal shifts, such as increased cycling or public transport usage. Additionally, the SMI does not currently account for the availability or quality of sustainable transport infrastructure (e.g., cycling lanes or rail coverage). Finally, the weighting scheme, while grounded in emission-related priorities, could be further refined or adapted to different territorial contexts. These limitations are consistent with known challenges in urban mobility indicator design, where data availability often conditions the scope of sustainability metrics [17].

Municipal Structure Index (MSI) Although the subindicator provides a useful first approximation, it presents some limitations:

- In small municipalities or those with non-consolidated urbanization, urban areas may not be correctly detected by the CLC. Similarly, land use may be misclassified—for example, a linear urban area next to a road may be mistakenly identified as infrastructure.
- Municipalities with a single urban core and large rural extensions may appear advantaged if green surface weight is not limited. A low weight was applied to mitigate this, but specific cases should be reviewed individually for more precise results.
- The subindicator does not consider industrial zones or actual accessibility to green spaces per person.
- Contaminating zones such as landfills or mining complexes are not currently penalized, although they could be, since they have a significant negative environmental impact.

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All web references were revised and their validity confirmed as of June 20, 2025, at 15h.

APPENDIX

A.1 EURO Standards and DGT Labels

Table 4: EURO EMISSION STANDARDS AND DGT LABELS – DIESEL VEHICLES

Standard	Year	NOx limit (mg/km)	DGT Label
Euro 1	1992	Not regulated	None
Euro 2	1996	500	None
Euro 3	2000	500	None
Euro 4	2005	250	B
Euro 5	2010	180	B
Euro 6	2014	80	C

Source: Author's elaboration based on EURO emission standards.

Table 5: EURO EMISSION STANDARDS AND DGT LABELS – PETROL VEHICLES

Standard	Year	NOx limit (mg/km)	DGT Label
Euro 1	1993	Not regulated	None
Euro 2	1997	250	None
Euro 3	2001	150	B
Euro 4	2005	80	C
Euro 5	2009	60	C
Euro 6	2014	60	C

Source: Author's elaboration based on EURO emission standards.

A.2 Other Environmental Labels

Table 6: ALTERNATIVE DGT ENVIRONMENTAL LABELS

Label	Vehicle Type and Requirements
0	Pure electric vehicles (BEV), hydrogen vehicles. Zero local emissions.
ECO	Plug-in hybrids with less than 40 km electric range, non-plug-in hybrids, natural gas or LPG vehicles.

Source: Author's elaboration based on DGT data and EURO emission standards.

A.3 Formula for the Biyiud Sustainability Indicator

Equation 8 presents the full formula used to compute the Base Sustainability Score (BSS-City) for each municipality i. This score is composed of five elements:

- $\text{Eco}_{\text{DE},i}$: the EcoScore for energy decarbonization, based on changes in energy-related CO_2 emissions.
- $\text{Eco}_{\text{DNE},i}$: the EcoScore for non-energy decarbonization, accounting for emissions reductions from other consumption sources (e.g., goods or services).
- $\text{IMS}_{\text{norm},i}$: the normalized value of the Sustainable Mobility Index (SMI), which measures the environmental impact of the local mobility model.
- $\text{IEM}_{\text{norm},i}$: the normalized value of the Municipal Structure Index (MSI), which evaluates the municipality's urban density and green space ratio.
- $\sum \text{Eco}_{\text{P},i}$: the total of all participation-based EcoScores from local actors (residents, companies, institutions) within municipality i.

Each term is computed independently using standardized methods and aggregated monthly into the overall BSS-City value, which supports comparative analysis across municipalities.

$$\text{BSS-City}_i = \text{Eco}_{\text{DE},i} + \text{Eco}_{\text{DNE},i} + \text{IMS}_{\text{norm},i} + \text{IEM}_{\text{norm},i} + \sum \text{Eco}_{\text{P},i} \quad (8)$$

A.4 Arcade Script for CLC Land Cover Classification in ArcGIS Pro

```
var codi = $feature.Code_18;
var urbans = ['111', '112', '121',
    '123', '133'];
var zVerdaUrb = ['141'];
var contaminants = ['131', '132',
    '134'];
var infraestructures = ['122', '124',
    '131', '132', '134', '142'];
var verds_oberts =
    ['211','212','213','221','222','223',
                    '231','241','242',
                    '243','244','311',
                    '312','313','321',
                    '322','323','324',
                    '331','332','333',
                    '334','335','411',
                    '412','421','422',
                    '423','511','512',
                    '521','522', '523'];
if (Includes(urbans, codi)) {
 return "Espais Urbans";
} else if (Includes(zVerdaUrb, codi)) {
    return "Zona Verda Urbana";
} else if (Includes(contaminants,
    codi)) {
    return "Zones Contaminants";
} else if (Includes(infraestructures,
    codi)) {
    return "Infraestructures";
} else if (Includes(verds_oberts,
    codi)) {
    return "Zones Verdes i Espai Obert";
} else {
    return "Altres";
}
```

Listing 1: Arcade code used for classifying CLC codes into land categories

A.5 Selected municipalities and their resuts on MSI and SMI subindicators

Table 7: MUNICIPAL STRUCTURE INDICATOR (MSI) VALUES FOR THE SAMPLE OF 17 MUNICIPALITIES

IC	MUN	CUS	US	INF	UGA	CA	GOS	TS	POP	DUE	DUE_L	DUE_N	GUR	GUR_L	GUR_N	MSI	MSI_N	QC
1001	alegría-dulantzi	1.257555	1.257555	NaN	NaN	NaN	18.688902	19.946456	2965	2357.750652	7.765887	0.463382	14.861305	2.763883	0.254011	0.421508	4.793572	Rural o molt dispers
46017	alzira	9.721084	9.721084	0.002550	NaN	NaN	100.861367	110.585001	47366	4872.501747	8.491568	0.526025	10.375526	2.431464	0.223445	0.465509	5.189582	Equilibrat semi-dispers
10023	arroyomolinos	6.479335	6.479335	0.396240	0.350798	NaN	129.085753	136.312126	826	127.482223	4.855791	0.212173	19.976827	3.043418	0.279715	0.225682	3.031135	Rural o urbanització dispersa
8019	barcelona	71.887215	71.887215	2.876454	6.277888	NaN	19.634156	100.675714	1686208	23456.298798	10.062937	0.661671	0.360454	0.307819	0.028172	0.534971	5.814739	Equilibrat semi-dispers
8089	gavà	6.311949	6.311949	0.186046	0.258991	0.471011	23.518976	30.746972	47961	7598.445727	8.935831	0.564375	3.767136	1.561746	0.143473	0.480195	5.321754	Equilibrat semi-dispers
26089	logroño	17.528307	17.528307	2.204809	0.866814	0.379996	57.993976	78.973903	150845	8605.794036	9.060307	0.575121	3.358042	1.472023	0.135223	0.487141	5.384269	Equilibrat semi-dispers
28079	madrid	217.333403	217.333403	66.918586	43.168520	6.665188	270.824052	604.909750	3422416	15747.307810	9.664488	0.627275	1.444751	0.893943	0.082067	0.518234	5.664104	Equilibrat semi-dispers
28080	majadahonda	10.520974	10.520974	1.769505	0.173889	NaN	26.028477	38.492845	73547	6990.512409	8.852452	0.557178	2.490489	1.250042	0.114811	0.468705	5.218341	Equilibrat semi-dispers
6083	mérida	13.469723	13.469723	5.699280	1.044541	1.293274	843.148882	864.655700	59894	4446.565104	8.400112	0.518130	62.673407	4.153767	0.381814	0.490867	5.417803	Equilibrat semi-dispers
1039	moreda de álava	0.200000	NaN	NaN	NaN	NaN	8.670963	8.670963	215	1075.000000	6.981006	0.395629	43.354816	3.792221	0.348569	0.386217	4.475950	Equilibrat semi-dispers
31201	pamplona/iruña	17.197071	17.197071	0.386780	2.310736	NaN	5.236519	25.131106	208243	12109.213258	9.401804	0.604600	0.438869	0.363857	0.033325	0.490345	5.413103	Equilibrat semi-dispers
28128	rozas de puerto real	0.632318	0.632318	NaN	NaN	NaN	28.914746	29.547064	581	918.841537	6.824201	0.382093	45.728176	3.844347	0.353362	0.376347	4.387119	Equilibrat semi-dispers
1052	samaniego	0.379984	0.379984	NaN	NaN	NaN	10.198064	10.578049	290	763.189216	6.638815	0.366090	26.838113	3.326406	0.305736	0.354019	4.186171	Equilibrat semi-dispers
8205	sant cugat del vallès	17.427283	17.427283	2.550278	0.578657	0.109940	27.631340	48.297498	98649	5660.606882	8.641463	0.538965	1.618726	0.962688	0.088389	0.448849	5.039644	Equilibrat semi-dispers
8295	vallirana	7.184167	7.184167	NaN	NaN	1.598596	15.064124	23.846887	15952	2220.438299	7.705910	0.458205	2.096850	1.130386	0.103809	0.387325	4.485929	Equilibrat semi-dispers
1059	vitoria-gasteiz	38.734715	38.734715	7.111573	1.615851	1.445138	228.057488	276.964764	257407	6645.382619	8.801828	0.552808	5.929393	1.935772	0.177865	0.477819	5.300374	Equilibrat semi-dispers
50297	zaragoza	99.797291	99.797291	26.997121	5.206693	5.747116	836.249190	973.997410	691037	6924.406365	8.842952	0.556358	8.431651	2.244071	0.206214	0.486329	5.376961	Equilibrat semi-dispers

IC	INE Code	**MUN**	Municipality	**CUS**	Corrected Urban Spaces
US	Urban Spaces	**INF**	Infrastructure	**UGA**	Urban Green Area
CA	Contaminant Areas	**GOS**	Green and Open Spaces	**TS**	Total Surface
POP	Population	**DUE**	Effective Urban Density	**DUE_L**	Log of DUE
DUE_N	Normalized DUE	**GUR**	Green/Urban Ratio	**GUR_L**	Log of GUR
GUR_N	Normalized GUR	**MSI**	Municipal Structure Index	**MSI_N**	Normalized MSI
QC	Qualitative Classification				

Source: Author's elaboration based on INE and CORINE Land Cover (CLC) data.

Table 8: SUSTAINABLE MOBILITY INDICATOR (SMI) VALUES FOR THE SAMPLE OF 17 MUNICIPALITIES

IC	MUN	POP	B	C	ECO	ZEV	NONE	EMI_T	EMI_A	VEHHAB	P GREEN	SMI	SMI_N
1001	Alegría-Dulantzi	2965	713	778	103	29	681	4106850	1782.486979	0.777066	0.057292	0.828467	5.566799
46017	Alzira	47366	9027	13864	1321	386	9241	59730550	1765.139336	0.714415	0.050445	0.833061	5.668546
10023	Arroyomolinos	826	309	151	16	1	407	1695400	1917.873303	1.070218	0.019231	0.784016	4.582348
8019	Barcelona	1686208	172922	422464	52220	27189	220678	1507083000	1683.002168	0.531057	0.088678	0.861551	6.299515
8089	Gavà	47961	7058	15278	1949	547	5531	50931850	1677.431413	0.633077	0.082205	0.862280	6.315658
26089	Logroño	150845	28149	35210	4597	977	25244	166279250	1765.603597	0.624330	0.059186	0.834031	5.690035
28079	Madrid	3422416	515845	762291	189170	65672	442607	3271123300	1655.774517	0.577249	0.128996	0.873466	6.563414
28080	Majadahonda	73547	12846	170575	53489	22823	8547	355392850	1325.000000	3.648000	0.284400	0.978000	8.890000
6083	Mérida	59894	16094	16353	1730	397	13040	85424900	1794.113076	0.794971	0.044672	0.823738	5.462061
1039	Moreda de Álava/Moreda Araba	215	75	67	11	2	96	459550	1830.876494	1.167442	0.051793	0.812636	5.216200
31201	Pamplona/Iruña	208243	40823	48747	5172	1614	33141	229034000	1768.643289	0.621855	0.052403	0.832467	5.655383
28128	Rozas de Puerto Real	581	2478	41909	8117	7703	2719	83560250	1328.000000	108.306000	0.251400	0.699000	2.710000
1052	Samaniego	290	89	62	13	2	125	540550	1857.560137	1.003448	0.051546	0.805180	5.051071
8205	Sant Cugat del Vallès	98649	11790	30870	4509	2520	11014	98304150	1619.428200	0.615343	0.115793	0.882761	6.769261
8295	Vallirana	15952	3221	5838	802	243	2912	22177400	1703.856792	0.815948	0.080286	0.853822	6.128348
1059	Vitoria-Gasteiz	257407	43921	59180	8098	1989	40029	268272300	1750.930380	0.595232	0.065835	0.839093	5.802139
50297	Zaragoza	691037	108857	153481	19432	4543	88884	653628300	1742.093620	0.542948	0.063900	0.841641	5.858577

IC	INE Code	**MUN**	Municipality	**POP**	Total Population
B	Vehicles with Label B	**C**	Vehicles with Label C	**ECO**	Vehicles with ECO Label
ZEV	Zero Emission Vehicles (Label 0)	**NONE**	No environmental label	**EMI_TOT**	Total CO_2 emissions (kg)
EMI_AVG	Avg. emissions per vehicle (kg)	**VEH/HAB**	Vehicles per capita	**P.GREEN**	Percentage of green vehicles
SMI	Sustainable Mobility Index	**SMI_N**	Normalized SMI		

Source: Author's elaboration based on DGT and INE data.