A Composite Suitability Framework to Identify Areas with Modal Shift Potential from Motorized Travel to Bike-Sharing in Barcelona: The Case of Bicing

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SHORT SUMMARY

This study develops a composite suitability framework integrating demand density and flow imbalance to identify areas in the Barcelona Metropolitan Area (AMB) with potential for modal shift from motorized travel to the Bicing bike-sharing system. Motorized origin–destination (OD) flows from traffic analysis zones (TAZ) are redistributed to a uniform rhombus grid and converted into bike-feasible demand using cycling travel times on the road network and a probabilistic bicycle-use model calibrated from observed bike-sharing trip durations. Based on this, demand density and flow imbalance are calculated for each rhombus and combined into a composite suitability score used to classify rhombuses into four categories: Priority, Serve but costly, Stable but weak, and Avoid. Comparison with the current Bicing service area shows strong overlap with Priority areas while revealing substantial high-suitability areas that remain unserved. The framework provides a transparent, scalable approach to identifying suitable areas for bike-sharing service provision.

Keywords: Bike-sharing; Demand density; Flow imbalance; Modal shift; Service area; Shared mobility

1. INTRODUCTION

Bike-sharing has emerged as a sustainable mobility solution to address energy, climate, and fuel challenges, but its expansion has also introduced growing operational, design, and management challenges (Shaheen et al., 2010; Shui & Szeto, 2020). Identifying suitable bike-sharing service areas is among the most significant challenges. For example, research has shown that identifying the location of bike-sharing stations (which represents the system's service area) is vital, as it is a critical design factor in meeting the demand (Shui & Szeto, 2020). Meanwhile, vehicle-sharing operators often focus on maximizing profits, which can negatively affect customer service by discontinuing service in unprofitable areas and underserving some users during significant imbalances or demand peaks (Hao & Martin, 2022). Conversely, expanding fleets to increase coverage may compromise the social benefits of vehicle-sharing systems (Hao & Martin, 2022). However, in this study, subzones with very high demand imbalances and very low demand densities are considered inefficient and unprofitable for operators and less reliable for users due to frequent empty or full stations. Therefore, service areas should be carefully defined to balance operator and user needs.

The literature shows that research on bike-sharing service areas and station locations generally follows two methodological approaches: mathematical and Geographic Information System (GIS) methods.

Integer Programming (IP) and bilevel programming are among the most commonly used models in studies employing mathematical approaches, although their methodological objectives vary. Many studies using mathematical approaches aim to minimize user, operational, and setup costs or maximize demand coverage (Cai et al., 2023; Lin et al., 2013; Mix et al., 2022). Other objectives mostly include addressing accessibility inequalities, and maximizing net revenue (Caggiani et al., 2020; Martinez et al., 2012). GIS-based approaches are also widely used, sometimes combined with multi-criteria decision-making (MCDM) or mathematical modelling. Similar to mathematical approaches, GIS studies pursue different objectives, such as focusing on bike-network coverage and residential demand zones, minimizing impedance, or reducing total system costs (Conrow et al., 2018; Garcia-Gutierrez et al., 2014; García-Palomares et al., 2012).

This research aims to identify areas within the Barcelona Metropolitan Area (AMB) that are most suitable for shifting trips from motorized modes to Bicing, the dominant bike-sharing system in Barcelona, by constructing a composite suitability framework. This study makes two key contributions to the bike-sharing planning literature. First, it proposes a suitability framework that integrates demand density and flow imbalance at the rhombus level, explicitly focusing on potential modal shift from private and public transport to bike-sharing. The rhombus grid is constructed based on the maximum walking distance to a bike-sharing station, allowing spatial variations beyond traffic analysis zones (TAZ) to be captured. Second, it provides an approach that considers both operator and user needs in evaluating the suitability of bike-sharing service areas.

2. METHODOLOGY

To identify where Bicing is currently active, the system's service area was delineated using official station coordinates from September 2025 (Ajuntament de Barcelona, 2025). Each station was assigned a rhombus-shaped coverage area with diagonals of 2b, where b = 400 m represents the maximum Manhattan walking distance to a station. The union of these areas defined the current Bicing service area. Using the same definition, the AMB was subdivided into a regular grid of rhombus cells (≈0.32 km² each), with centroids representing potential stations, and all subsequent analyses were conducted at this cell level rather than TAZ (see Figure 1). The term rhombus is used instead of square because the grid is aligned with the street network rather than geographic north, where equal walking distances along perpendicular streets produce diamond-shaped accessibility areas.

Land-use and mobility-related variables from OpenStreetMap (OpenStreetMap contributors, 2026) and population data from the georeferenced population dataset of Catalonia (Idescat, 2024) were assigned to each rhombus to construct origin and destination potentials representing trip generation and attraction capacity. These variables were allocated using an intersection-based approach: polygon features (e.g., population grid cells) were distributed proportionally by intersection area, while point features (e.g., transit stations) were counted within each rhombus. All variables were normalized to a 0–1 range and combined with equal weights. Origin potential was defined as the mean of population, employment, tourism origin (accommodation), and transit intensity, excluding activity intensity, as it primarily represents trip-attracting land uses. Destination potential was defined as the mean of population, employment, activity intensity (e.g., retail, services, and leisure), tourism destination (attractions), and transit intensity.

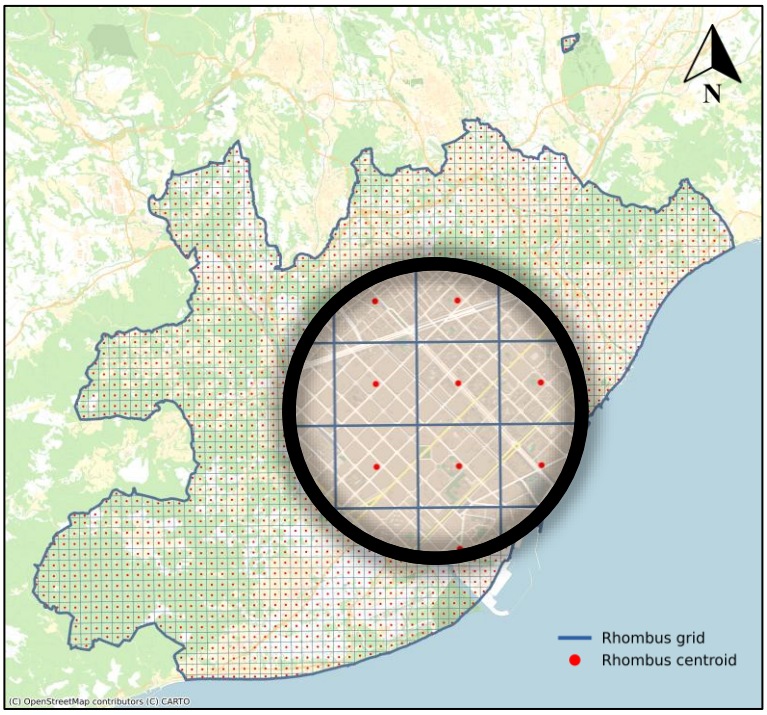


Figure 1: Rhombus grid covering the AMB with a zoomed detail

The zone-to-zone motorized OD matrix was obtained from the mobility model of the Autoritat del Transport Metropolità (ATM, 2019). The share of each zone covered by intersecting rhombuses was calculated (area fraction). Allocation probabilities were then derived from the product of this area fraction and the corresponding rhombus origin or destination potential. Each zone-to-zone trip value was then multiplied by the corresponding origin and destination probabilities to produce the rhombus-to-rhombus OD matrix.

Travel times were computed on the OpenStreetMap road network (OpenStreetMap contributors, 2026) using segment length and an assumed cycling speed of 15 km/h. Times were adjusted for infrastructure type (e.g., dedicated cycleways versus primary roads) and uphill slope using elevation data from the European Digital Elevation Model (European Environment Agency, 2016). The shortest travel time between rhombus centroids was calculated using a shortest-path algorithm. When network routing was not possible, travel time was approximated using Euclidean centroid distance multiplied by a calibrated detour factor, derived from a spatially balanced sample of 150 rhombuses and calculated as the median ratio of network to Euclidean travel times.

To estimate the likelihood of choosing the bicycle based on travel time, empirical trip durations from BiciMAD, Madrid's public bike-sharing system (Empresa Municipal de Transportes de Madrid, 2023), were used due to the lack of access to Bicing data. Trips outside the 1–60 minute range were removed as outliers, and a lognormal distribution was fitted to the remaining travel times. The dispersion parameter (σ) was retained, while the mean of the logarithm of travel time (μ) was recalibrated to match the Bicing benchmark mean of 12.7 minutes (Ajuntament de Barcelona, 2026). The calculated travel time for each rhombus OD pair was then converted into a continuous bicycle-use probability P_b using the calibrated distribution, where t denotes cycling travel time:

$$P_b = 1 - F_{\text{lognormal}}(t) \quad (1)$$

Shorter travel times correspond to a higher probability of choosing the bicycle; rhombus-level trip flows were multiplied by this probability to construct the bike-feasible OD matrix.

Using this OD matrix, demand density (*DD*) and flow imbalance (*I*) were computed for each rhombus. Demand density was defined as the total number of bike-feasible trips T_b (interzonal and intrazonal) divided by rhombus area *A* (km²), expressed in trips per day per km².

$$DD = \frac{T_b}{A} \quad (2)$$

Flow imbalance was calculated using interzonal trips only. For each rhombus, incoming (F_{in}) and outgoing (F_{out}) flows were aggregated, and imbalance was defined as their absolute difference divided by their sum, yielding a normalized ratio between 0 and 1, where higher values indicate stronger directional asymmetry:

$$I = \frac{|F_{out} - F_{in}|}{F_{out} + F_{in}} \quad (3)$$

Finally, a composite suitability score (*CSS*) was computed by combining normalized demand density (DD_{norm}, 0–1) with flow imbalance, defined as:

$$CSS = DD_{norm} \times (1 - I) \quad (4)$$

This formulation assigns higher scores to rhombuses with high demand and balanced flows. Rhombuses with zero bike-feasible trips were classified as inactive rhombuses (score = 0). For interpretation, rhombuses were classified into four groups using median thresholds of demand and imbalance: high demand–low imbalance (Priority), high demand–high imbalance (Serve but costly), low demand–low imbalance (Stable but weak), and low demand–high imbalance (Avoid).

3. RESULTS AND DISCUSSION

Bicing covers 59.24 km² (9.33% of the AMB), of which 97.3% lies within Barcelona city. This shows the system is highly concentrated in the city, with very limited extension into the wider metropolitan area, indicating expansion potential (see Figure 5).

Population is concentrated roughly 2–5 km from the city center (Plaça de Catalunya) and declines outward. Urban activity layers follow a broadly similar radial pattern: tourism and transit accessibility concentrate within 0–3 km, while employment and general activity extend across roughly the 3–10 km distance bands. Together, these results indicate a strong central concentration of demand-generation and attraction potential in Barcelona.

The calibrated lognormal distribution yields parameters $\sigma = 0.6657$ and $\mu = 2.3201$, reproducing the Bicing mean trip duration of 12.7 minutes (see Figure 2). The distribution is strongly right-skewed (skewness = 2.656), indicating that most trips are short with a long tail of longer durations. The calibrated median detour factor is 1.504, meaning cycling routes are on average about 50%

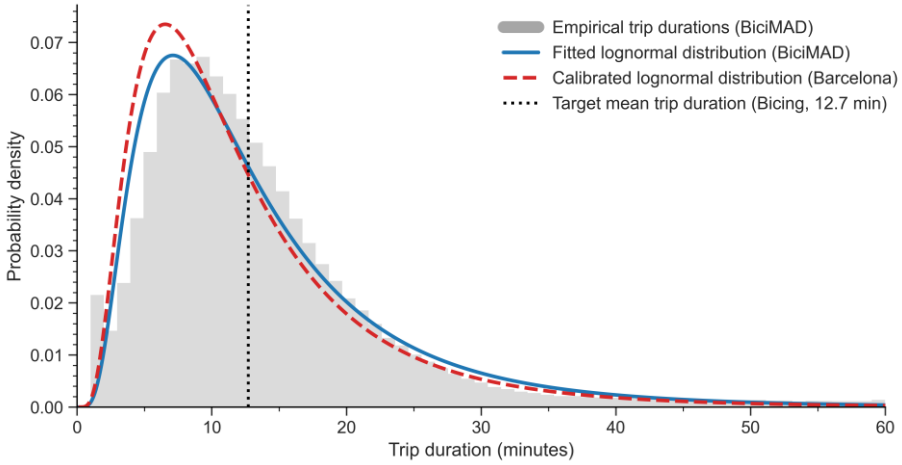


Figure 2: Calibration of Bike-Sharing Trip Duration Distribution

longer than straight-line distances. This factor is applied in Euclidean fallback cases when network routing is unavailable.

Applying the calibrated probabilistic model to the average weekday rhombus-to-rhombus OD matrix identifies 1,289,487 bike-feasible trips out of 5,064,781 motorized trips, indicating that about one quarter of existing motorized trips fall within a realistic cycling range.

Bike-feasible demand density is highly concentrated spatially, with a mean of 3,720 trips per day per km² and a median of 292, indicating strong skewness toward high-intensity rhombuses. About 89% of rhombuses are active (bike-feasible trips > 0). Flow imbalance averages 0.533, and 48.7% of rhombuses show high imbalance (> 0.5), reflecting notable asymmetry in potential cycling flows. Radial analysis shows a clear distance-decay pattern: demand density peaks within 0–3 km of the city center and declines with distance (see Figure 3a), while imbalance is lowest within the first 2 km and increases outward (see Figure 3b), indicating strong central concentration of cycling potential, with outer areas characterized by lower demand and greater flow asymmetry.

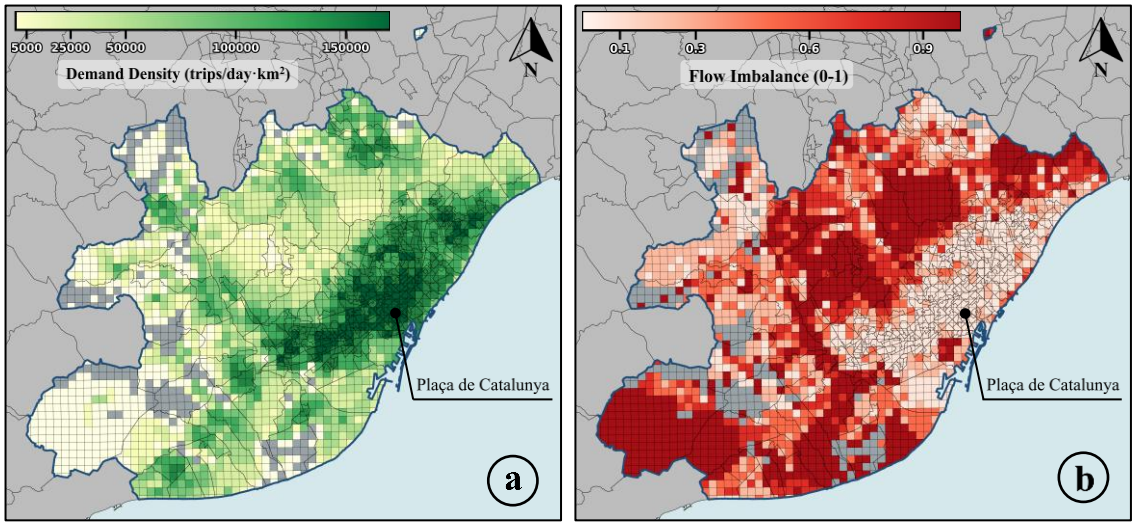


Figure 3: Spatial distribution of (a) demand density and (b) flow imbalance across the AMB

The composite suitability classification highlights the spatial structure of potential service configuration (see Figure 4 and Table 1). About 30.6% of rhombuses fall into the Priority category, representing the most favorable areas for service provision, while a similar share is classified as Avoid, indicating structurally weak and operationally challenging areas. The remaining rhombuses are divided between Serve but costly (14.1%), indicating strong cycling potential but requiring repositioning, and Stable but weak (14.1%). Radial analysis shows that Priority areas concentrate within 0–10 km of the city center, while Avoid and inactive areas are more common beyond 10 km, suggesting that the most suitable areas for bike-sharing are concentrated within this 0–10 km range.

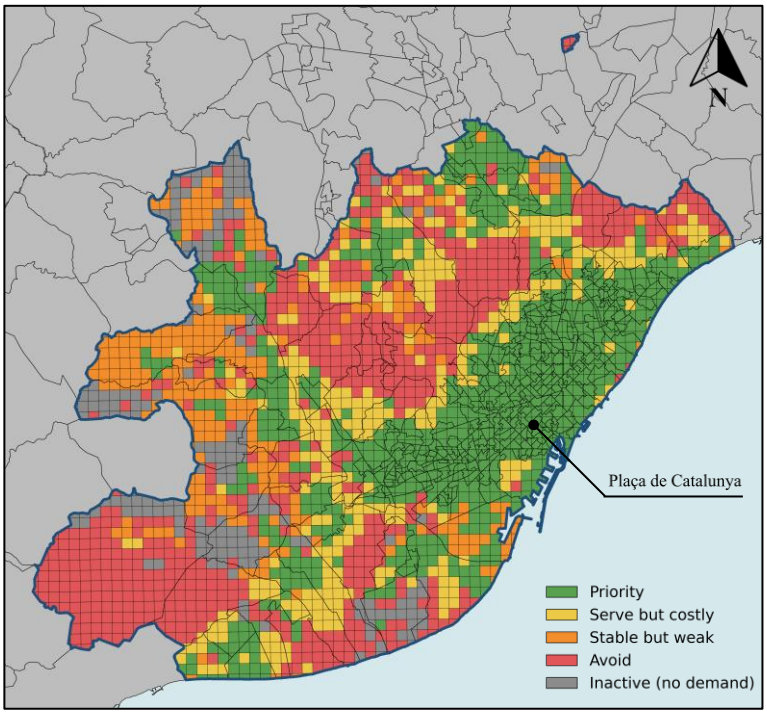


Figure 4: Spatial classification of rhombuses according to the composite suitability score

Table 1: Summary of suitability categories across the AMB

Category	Rhombuses	Area (km^2)	Share of AMB (%)
Priority (High demand & low imbalance)	668	207.25	32.6
Serve but costly (High demand & high imbalance)	308	97.42	15.3
Stable but weak (Low demand & low imbalance)	308	83.73	13.2
Avoid (Low demand & high imbalance)	667	193.23	30.4
Inactive (Zero demand)	231	53.53	8.4
Total	2182	635.16	100.0

Because the Priority category represents areas with high demand and balanced flows, it provides the most appropriate benchmark for comparison with the current Bicing service area. Although spatially concentrated, the Priority area (207.25 km²) is much larger than the existing service area (59.24 km²). About 93.5% of the current service area overlaps with Priority rhombuses, while only 26.7% of the Priority area is covered, leaving substantial favorable territory unserved (see Figure 5). While the current service area is concentrated around the city center and remains compact, the Priority area extends further, particularly toward the north, northeast, and parts of the southwest. The comparison indicates that the current service area captures only part of the most suitable areas for bike-sharing, while the remaining uncovered areas represent potential for expansion that could be implemented progressively rather than through immediate large-scale expansion.

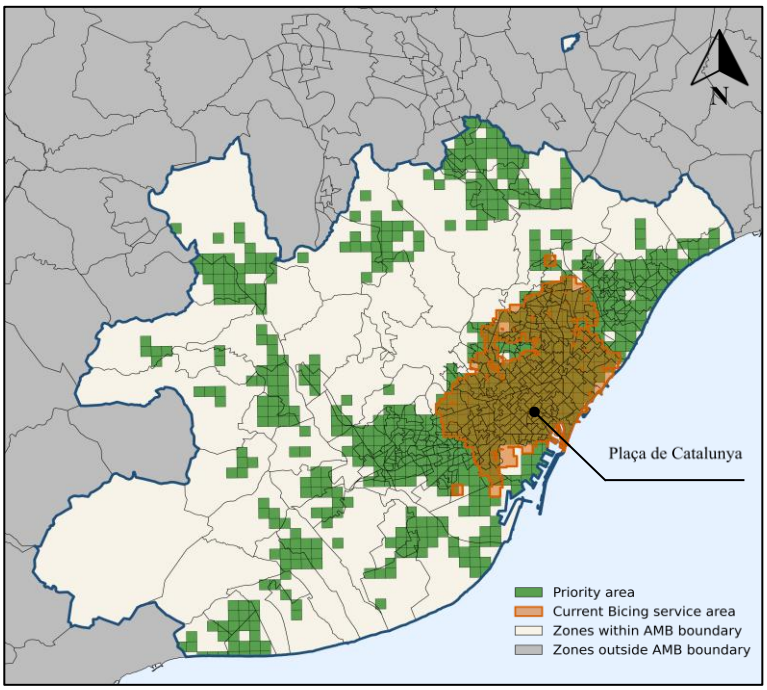


Figure 5: Comparison of the current Bicing service area and Priority areas

4. CONCLUSIONS

This study developed a suitability framework to identify areas within the AMB with potential for modal shift from motorized travel to the Bicing bike-sharing system. Motorized OD flows were redistributed from TAZ to a uniform rhombus grid and transformed into estimates of bike-feasible demand using cycling travel times on the road network and a probabilistic bicycle-use model calibrated from observed bike-sharing trip durations. Demand density and flow imbalance were then calculated for each rhombus and combined into a composite suitability score used to classify the study area into suitability categories.

The findings show a strong central concentration of cycling potential: demand density declines with distance from the city center, while flow imbalance increases toward peripheral areas. About one-third of rhombuses fall into the Priority category, mainly within 0–10 km of the city center. Comparing the Priority areas with the current Bicing service area shows strong overlap, with over

90% of the existing service area falling within Priority areas. However, only about one-quarter of the Priority area is currently served, indicating substantial expansion potential that could be implemented progressively.

The findings highlight two main points. First, relying solely on financial or short-term operational criteria may overlook areas with structurally strong and balanced demand. Second, integrating demand density and flow balance at a detailed spatial scale helps identify suitable service areas more precisely and reliably.

The study also has some limitations. One is that the analysis considers only motorized trip patterns and does not include existing non-motorized trips (e.g., walking and cycling), which could improve the representation of short-distance mobility and the estimation of substitution potential. Another is that the methodology evaluates spatial suitability but does not explicitly optimize service areas by considering user costs, agency costs, and profits. Future research could address this through optimization frameworks targeting variables such as station density and repositioning frequency to complement the suitability approach and identify more efficient and equitable bike-sharing service areas.

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