

<https://doi.org/10.1038/s44333-026-00104-5>

Modal synergies between dockless electric bikes and rail transit in Lausanne Switzerland

Check for updates

Dylan Moinse & Virginie Lurkin

The integration of cycling with public transport is a key lever for reducing car dependency. Despite the expansion of shared micromobility, empirical evidence on its integration with rail remains limited in medium-sized European cities. This study develops a framework to assess integration between dockless shared e-bikes (DBS) and rail transit in Lausanne, Switzerland. Using high-resolution operator data, we reconstruct e-bike trajectories and identify trips compatible with bike-and-ride transfers through a spatiotemporal “Inside Station Catchment Area” (ISCA) proxy. Descriptive and accessibility analyses characterise DBS–rail integration and quantify station catchment extensions relative to walk-and-ride scenarios. Findings indicate that a substantial share of DBS trips supports rail access and extends station catchments. OLS models across temporal periods identify the key accessibility, land use, and sociodemographic determinants of potential intermodal behaviour. The ISCA framework offers a transferable approach for evaluating first- and last-mile solutions, with implications for station-area planning and integrated mobility policy.

Promoting a substantial shift toward sustainable modes of transport has become a central objective of mobility and climate policies. However, reducing car dependency and greenhouse gas emissions requires not only improvements in public transport supply, but also effective access solutions capable of making transit a competitive alternative to private car use. In this regard, expanding the effective station accessibility zones, commonly referred to as transit catchment areas, constitutes a key challenge for both researchers and practitioners¹. The literature consistently shows that improvements to public transport alone are insufficient to significantly reduce private car use, particularly in dispersed or low-density territories shaped by urban sprawl². Beyond infrastructure or service quality, the ability of travellers to conveniently reach stations and connections largely determines modal shift^{3,4}. Transit-oriented development (TOD) strategies aim to strengthen the relationship between public transport and the built environment, but their operationalisation remains predominantly focused on walking, typically assumed to define catchment radii of 400–800 m^{5,6}. As a result, extending station accessibility beyond walking distances has emerged as a prerequisite for increasing transit ridership. Bike-and-ride opportunities offer one of the most promising levers in this regard. Combining cycling with public transport enables users to cover substantially longer distances than walking at low energy cost⁷, thereby extending the spatial reach of transit services up to several kilometres^{8,9}. This potential has led to the development of extended planning frameworks such as Bicycle-based TOD^{10,11}, Micromobility-friendly TOD¹², or interestingly TOD-based 15-

Minute Cities¹³. In recent years, the rapid rise of micromobility has further diversified intermodal access possibilities. Electric bikes, whether privately owned or accessed through sharing schemes, offer performance levels comparable to conventional bicycles^{14,15}. Among these emerging modes, dockless e-bikesharing (DBS) holds particular promise for first- and last-mile connectivity, as its spatial flexibility removes the infrastructural constraints associated with station-based systems and allows access to transit in areas where walking alone is insufficient. Despite this potential, empirical research explicitly examining the integration of DBS with public transport remains limited. Existing studies have largely focused on walk-and-ride or bike–train combinations using personal bicycles, leaving shared dockless systems comparatively understudied^{16,17}. Moreover, research on micromobility services has primarily emphasised safety issues rather than mobility behaviour¹⁸, despite growing evidence that such modes are likely to play an increasingly central role in multimodal chains^{14,19}. In the Swiss context, both the Federal Statistical Office and the Federal Office for Spatial Planning identify the first- and last-mile (FLM) challenge as a strategic analytical priority²⁰. In addition, existing empirical evidence remains geographically imbalanced, with a strong concentration on large metropolitan areas in East Asia and North America, while European medium-sized cities are underrepresented²¹. This limits the external validity of current findings and leaves important blind spots regarding regional rail systems and non-metropolitan contexts²². From a methodological perspective, research continues to rely predominantly on surveys and interviews, despite the

Department of Operations, Faculty of Business and Economics (HEC Lausanne), University of Lausanne, Lausanne, Switzerland. e-mail: virginie.lurkin@unil.ch

increasing availability of high-resolution mobility data. Leveraging real-world trip traces, therefore, represents a key opportunity to better understand how emerging modes such as DBS integrate with public transport networks²³. Methodologically, explaining the determinants of potential intermodal DBS behaviour calls for regression frameworks capable of handling count outcomes and continuous mobility measures within a consistent comparative structure. Global specifications such as Poisson generalised linear model (GLM) and ordinary least squares (OLS) provide parsimonious and interpretable estimates of average associations between contextual factors and mobility outcomes, and have been widely applied in shared micromobility and transit integration research^{24,25}. Geographically weighted regression (GWR) extends this framework by allowing coefficients to vary across space²⁶, but its added value depends on whether spatial non-stationarity is pronounced enough to justify the additional complexity²⁷. When calibrated bandwidths approach the full sample size, local estimation converges toward the global solution, and the inferential gain from spatial weighting is negligible. Whether heterogeneity is substantial enough to warrant local modelling is therefore an empirical question, addressed here by comparing model fit across global and spatially varying specifications. Among the emerging literature on synergies between shared micromobility services and public transport networks, several studies have applied spatial regression approaches in large metropolitan contexts, including Beijing, Nanjing, Shanghai, and New York City^{24,28–31}. More recent contributions include multiscale GWR and geographically and temporally weighted regression, which incorporate multiple spatial or temporal scales^{25,32}. These approaches document substantial spatial heterogeneity in large Asian and North American cities, but it remains an open question whether comparable heterogeneity exists in compact European metropolitan contexts with more uniform transit coverage. Mobility demand for shared e-bikes further varies across time of day, and temporal segmentation allows the hierarchy of determinants to be examined separately across commuting and leisure contexts²⁵.

This study examines whether dockless bikesharing (DBS) functions as an access and egress mode to rail transit and thereby expands public transport accessibility. We analyse *Bird* shared e-bike operations in Lausanne, including the University of Lausanne campus. Using trip-level DBS data, we identify potential bike-and-ride segments connecting with rail stations through an ‘Inside Station Catchment Area’ (ISCA) proxy for intermodality.

The objectives of this paper are to (i) quantify the extent of potential DBS–public transport intermodality, (ii) describe its spatial and temporal patterns around rail stations, (iii) examine and assess these patterns using accessibility, built environment, land use, and sociodemographic factors, and (iv) discuss implications for integrated mobility and transit-oriented planning.

The primary contribution of this study is the development of a transferable analytical framework to detect, quantify, and explain potential integration between shared micromobility and rail transit. The DBS dataset and descriptive analyses serve to validate the framework empirically, while global GLM and OLS models estimated across temporal periods are used to explain the determinants of potential intermodal behaviour, with geographically weighted specifications serving as robustness checks to assess the degree of spatial non-stationarity.

Methods

The methodological framework is designed to support a single analytical objective: Identifying and characterising potential dockless e-bike integration with rail transit. Data sources, descriptive metrics, and modelling tools are therefore presented as complementary components of this unified pipeline. Given the limitations of shared micromobility datasets—namely, heterogeneous GPS accuracy, missing values, noisy distance records, and the absence of continuous trajectories—our approach combines reproducible data cleaning procedures, network-based routing, and complementary spatial modelling. The workflow begins with systematic validation of numeric, temporal, and geographic fields, followed by network-constrained

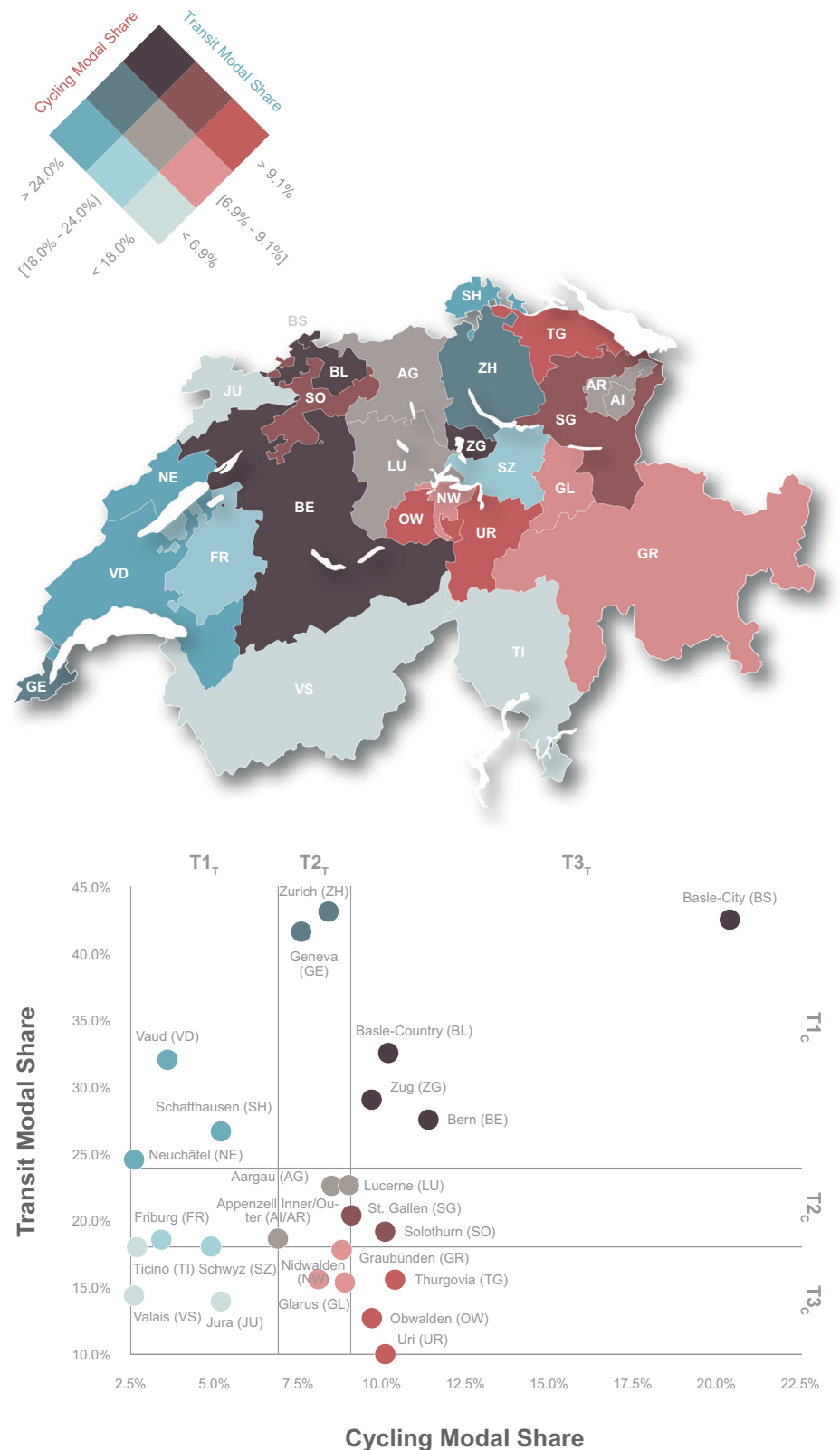
route reconstruction and the detection of trips compatible with bike-and-ride behaviour. Bike-and-ride identification based on large-scale spatial data tends to overestimate actual intermodality relative to smart-card or trajectory-based methods. To address this limitation, we introduce the concept of ‘Inside Station Catchment Area’ (ISCA) trips, defined as DBS trips whose endpoints fall within station-accessible areas and occur during public transport operating hours. ISCA thus represents a proxy for potential intermodality rather than a direct observation of transfers. We first introduce our case study, then describe the data cleaning workflow and the reconstruction of network-constrained routes using *OpenTripPlanner*. We subsequently detail the spatiotemporal procedure used to extract ISCA trips. Finally, to investigate the influence of accessibility, built environment, and sociodemographic factors on shared e-bike usage, we estimate a set of regression models, including global specifications (GLM and OLS) and GWR models across temporal slices. The latter are used as a diagnostic tool to assess whether relationships exhibit meaningful spatial and temporal heterogeneity beyond global model assumptions, and to evaluate the added value of local modelling in this context.

Case study

The extent to which DBS services integrate with public transport depends on local governance, the spatial logic of deployment, and the availability of empirical data to observe usage at scale. The Lausanne–Morges agglomeration (PALM) provides a relevant setting: It combines a dense rail backbone with persistent short-distance car use, and has placed multimodality and station accessibility at the core of its strategic planning. In line with these objectives, Lausanne introduced its first dockless electric bikesharing (DBS) service in April 2024. Operated by *Bird*, the system runs 24/7 and relies on virtual parking zones. Since launch, coverage has expanded across most of the city and the University of Lausanne (UNIL) campus, offering an opportunity to examine whether DBS availability can support transfers to rail at the metropolitan scale. Within the canton of Vaud, the Lausanne–Morges metropolitan area has been structured since 2007 through the Lausanne–Morges Agglomeration Project (PALM), integrated into the *Plan Directeur Cantonal* (PDCn) under measure R11³³. Because DBS flows are primarily concentrated within Lausanne and the Dorigny campus (UNIL), we adopt a more granular perimeter and focus on four PALM sectors (*schémas directeurs*): SDCL, SDOL, SDEL, and SDNL, excluding *Région Morges* to ensure a more focused analysis. PALM accounts for 286,000 inhabitants and 210,000 jobs (37% of the cantonal population and 48% of cantonal employment)³³. Within our study area, a dense and integrated public transport network provides extensive regional and local coverage. The rail backbone is structured around the *RER Vaud*, operated by SBB CFF FFS since 1999, with Lausanne, Renens, and Prilly–Malley acting as major interchange hubs. At the local scale, the TL network complements rail services through two metro lines (M1, M2), trolleybus and bus lines, and the LEB railway line integrated into the TL system. The fare system is integrated under *Mobilis*, enabling seamless transfers across operators and modes. According to the Swiss Mobility and Transport Microcensus (MTMC 2021), private cars remain the dominant mode in Switzerland (69% of trips), while public transport accounts for 20%³⁴. Car ownership is widespread (78% of households own at least one car), and bicycle ownership is also substantial (61% of households)³⁴. Cycling trips, including bicycles and e-bikes, remain shorter than average daily travel distances, with marked regional differences across cantons. In Vaud, the public transport modal share remains lower than in leading Swiss cantons such as Basel-Stadt and Zurich (Fig. 1)^{34,35}.

Mobility is a key climate challenge in Vaud: Transport accounts for a substantial share of cantonal greenhouse gas emissions³⁶. Despite a dense rail network, short car trips remain frequent in the Lausanne agglomeration³⁷, indicating that access and egress conditions still constrain public transport use. At the same time, Lausanne has a comparatively low motorisation rate³⁸, and multimodality is relatively common, with trips often involving more than one segment³⁹. The rapid uptake of e-bikes has further reshaped cycling dynamics and motivates renewed attention to

Fig. 1 | Bivariate map of cycling and public transport commuting shares in Switzerland. The figure presents the joint distribution of cycling and public transport commuting modal shares across the 26 Swiss cantons, based on data from the 2021 Mobility and Transport Microcensus (MTMC). The upper choropleth map encodes two variables simultaneously using a bivariate colour scheme. The transit modal share dimension is represented in blue, with three classes: Below 18.0% (light blue), 18.0–24.0% (medium blue), and above 24.0% (dark blue). The cycling modal share dimension is represented in red, with three classes: Below 6.9% (light red), 6.9–9.1% (medium red), and above 9.1% (dark red). Combinations of high values on both dimensions appear in dark purple-grey. Cantons are labelled with their official two-letter abbreviations. The lower scatter plot positions each canton according to its cycling modal share (horizontal axis, 2.5–22.5%) and transit modal share (vertical axis, 10.0–45.0%), with each canton represented by a filled circle coloured according to the same bivariate scheme as the map. Notable patterns include Basle-City (BS) as an outlier combining the highest cycling share (above 20%) with a high transit share, while Vaud (VD) and Neuchâtel (NE) exhibit high transit shares alongside low cycling shares.



bicycle-based station accessibility^{37,40}. To support modal shift, national and cantonal strategic documents stress the need to improve station accessibility and to facilitate intermodality between transit, walking, and cycling⁴¹. In Vaud, a large majority of residents and jobs are located within a few kilometres of a railway station, a range well suited to cycling as a feeder mode^{42,43}. Mobility and land use policies in Switzerland are increasingly shaped by binding climate objectives at national, cantonal, and municipal levels.

Switzerland's second *Nationally Determined Contribution* commits to reducing greenhouse gas emissions by at least 65% by 2035 relative to 1990 levels⁴⁴. This trajectory is reinforced by the *Federal Act on Climate Protection, Innovation and Energy Security* (2022), which sets sector-specific targets for transport, including a 57% reduction by 2040 and net-zero emissions by 2050⁴⁵. At the cantonal scale, the *Perspectives Mobilité 2050* for the Canton of Vaud identifies only the most ambitious scenario ('Sobriety',

Fig. 2 | Parked Bird DBS around two main multimodal hubs. Pictures of parked Bird DBS around Gare de Lausanne and Gare Prilly-Malley multimodal hubs. The two photographs illustrate the physical presence of Bird dockless electric bike-sharing (DBS) vehicles at two multimodal hubs in the Lausanne metropolitan area. **A** Two Bird electric bicycles are parked in front of one of the entrances of Gare de Lausanne railway station. **B** Several Bird electric bicycles are parked at Malley metro station, near Gare Prilly-Malley, representing a multimodal hub located in the western part of the city. Both photographs show the ‘semi-floating’ operational model of the Bird service, in which bicycles may be parked within designated zones.



S3) as compatible with long-term climate commitments, projecting a substantial increase in rail and cycling shares alongside a decline in car use⁴⁶. These orientations are embedded in the *Plan Directeur Cantonal*, which aims to reduce the modal share of private cars to 50% by 2050³³, and in the cantonal climate strategy. At the municipal level, Lausanne has committed to achieving zero direct mobility-related emissions by 2030⁴⁷. Cycling plays a central role in this transition. The *Federal Act on Cycling Infrastructure*, in force since 2023, requires all cantons and municipalities to develop and implement comprehensive cycling networks by 2042^{45,48}. In Vaud, the *Plan Directeur Cantonal* and the *Plan Climat Vaudois* target a tripling of cycling distance travelled and a modal share of at least 10% by 2035^{33,49}. Lausanne’s climate strategy further reinforces this ambition, aiming for a major expansion of cycling activity by 2030⁴⁷. Rail transport constitutes the backbone of Switzerland’s low-carbon mobility strategy. The *Programme de développement stratégique de l’infrastructure ferroviaire* (PRODES) plans a substantial increase in service frequency by 2035, with half-hourly or quarter-hourly services on most main lines⁵⁰. This expansion is integrated into the *SBB CFF FFS 2030 Strategy*, which explicitly emphasises seamless FLM access, notably through improved active mobility connections and bicycle parking around stations⁵¹. At the cantonal and metropolitan levels, rail-oriented strategies place strong emphasis on intermodality. The *Stratégie ferroviaire vaudoise* seeks to anchor rail at the core of daily mobility, supported by enhanced walking and cycling connectivity⁴³. National and regional planning documents similarly highlight the Lausanne–Geneva metropolitan area as a priority for strengthening active modes as feeder services to mass transit^{37,41}. Within this framework, intermodal interfaces and short-distance access to stations are identified as key levers for achieving modal shift^{33,52}. Together, these strategic orientations underscore the central role assigned to cycling, rail transport, and their integration within Swiss climate and mobility policies. In this context, shared micromobility services are increasingly viewed as promising instruments to address FLM constraints and to operationalise intermodality objectives in dense and topographically constrained urban regions such as Lausanne.

Implementation of a semi-floating e-bike service in Lausanne

The Bird shared e-bike service was launched in Lausanne on April 22, 2024, as a pilot project supported by the municipal administration^{53–55}. The initial fleet (100 e-bikes) expanded to 300 units by May 2024⁵³, and the service was extended to the UNIL campus in October 2024⁵⁶. Users can travel within the operational perimeter subject to parking rules and geofenced constraints (Fig. 2).

Trips are made on app-unlocked, GPS-enabled electric-assist bicycles with geofenced parking. The operation follows a *semi-floating* model: Users can start and end trips without physical docks, but parking is restricted to predefined zones (Fig. 3), some of which require locking to designated racks⁵⁷. This hybrid configuration aims to combine the flexibility of dockless systems with improved management of public space and safety. The service complements the existing station-based system in the Lausanne–Morges area (*PubliBike Velospot*)^{58,59}. The geofencing scheme distinguishes functional zones (operation, mandatory parking, low-speed areas, and prohibited areas) to ensure orderly integration into the urban environment^{56,58}.

Pricing follows a standard pay-per-use model (unlock fee and per-minute fare), complemented by subscription options and occasional promotions⁶⁰.

Dockless bikesharing data collection

The dataset analysed in this study originates from the Bird DBS system operating in Lausanne and the UNIL campus and was made available through a research collaboration between the University of Lausanne (HEC Lausanne) and the operator. Bird granted secure access to anonymised operational data extracted from its backend infrastructure. Data access, confidentiality, and use were governed by formal agreements, and data handling complied with applicable data protection requirements.

The dataset covers 459 consecutive days (April 22, 2024–July 24, 2025) and comprises 63,322 ride records (Supplementary Fig. 2). It includes anonymised user identifiers, trip metadata, and spatiotemporal information (Table 1). Each record corresponds to a completed ride and provides start and end coordinates (WGS84), start and end timestamps (ISO 8601), and a distance variable (cleaned_distance) produced after operator preprocessing. Descriptive exploration indicates 7364 unique users over the observation period, with heterogeneous usage intensity (median use markedly lower than the mean). The dataset provides sufficiently granular origin and destination information to support routing and network-based analyses, while the absence of continuous GPS trajectories limits analyses to start and end locations and inferred routes. This description motivates the analytical framework, which details the data cleaning, routing procedures, and the identification of segments potentially connected to public transport networks.

Data cleaning workflow

All cleaning and validation steps were performed using reproducible Python workflows, combining trip-level exclusions with geo-enabled consistency

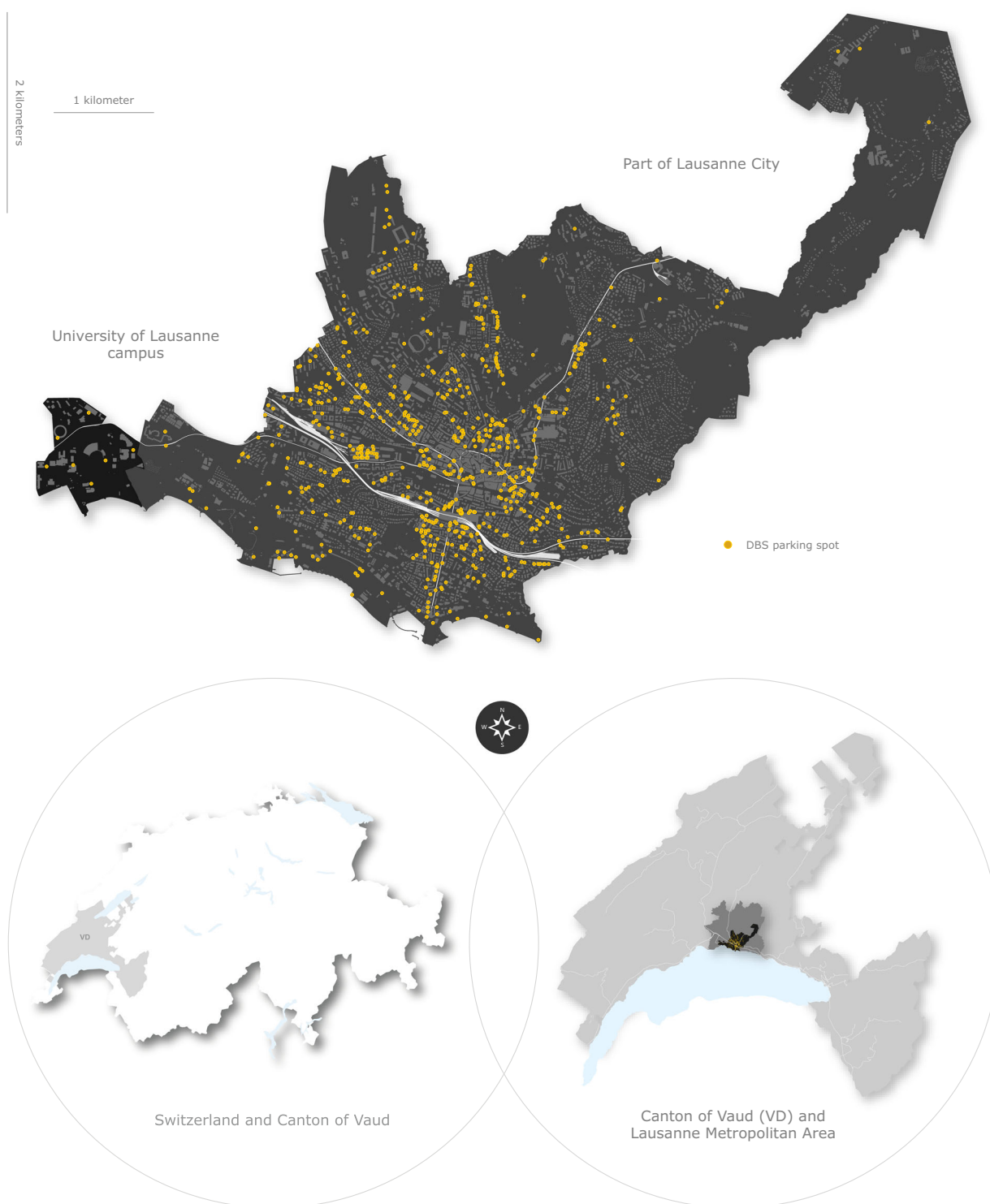


Fig. 3 | Spatial distribution of DBS parking spots within the study area. The figure presents the location of dockless bikesharing (DBS) designated parking spots across the main part of the Lausanne city area. The upper panel displays the spatial distribution of DBS parking spots across the Lausanne administrative area. Yellow-filled circles indicate individual DBS parking spots. The dark grey detached polygon to the left indicates the University of Lausanne (UNIL) campus

of Dorigny. Parking spots are visibly concentrated in the central city and along major transit corridors, with sparser coverage in peripheral and residential areas. The lower-left inset shows the location of the Canton of Vaud (VD) within Switzerland, highlighted in light grey, providing national geographic context. The lower-right inset displays the Lausanne municipal and metropolitan areas in the Canton de Vaud.

checks. Ten sequential exclusion criteria were applied to remove incomplete, inconsistent, or implausible records (Supplementary Fig. 1).

Missing values (df_cleaning_01). We removed all records containing at least one missing field across identifiers, timestamps, coordinates, the city label, or the distance variable. This step eliminated 1385 trips (2.19%) and 44

users (0.60%), leaving 61,935 trips and 7320 users. Missingness was primarily concentrated in the distance-related timestamp `ride_completed_at`. **Duplicate trip identifiers** (df_cleaning_02). To preserve a strict one-to-one mapping between rows and trips, we screened the dataset for repeated `ride_id` values. No duplicates were detected, leaving counts unchanged at

Table 1 | Raw data description

ID	Variable	Unique values
General		
	Number of rides	63,320
	Number of users	7364
	Sum of travelled distance (km)	7444
	Sum of days	460
Columns		
01	dt	459
02	start_city	2
03	ride_id	63,320
04	user_id	7364
05	start_longitude	59,878
06	end_longitude	60,919
07	start_latitude	58,432
08	end_latitude	59,848
09	ride_started_at	55,235
10	ride_completed_at	53,563
11	cleaned_distance	824

61,935 trips and 7320 users. Ensuring identifier uniqueness safeguards valid aggregation and supports reliable standard-error estimation. *Date-format validation* (df_cleaning_03). We checked that all timestamp fields—dt, ride_started_at, and ride_completed_at—were well-formed and parsable, adhering to ISO-compliant formats and valid calendar values. No records required removal, confirming consistent timestamp formatting. Counts therefore remained 61,935 trips and 7320 users. *Temporal consistency* (df_cleaning_04). We assessed each trip for plausibility by verifying that timestamps fell within the study window (April 22, 2024 to July 24, 2025) and that trip durations were neither unrealistically short (below a minimal operational threshold) nor excessively long (beyond a conservative upper bound). No additional records were removed at this stage. *Textual geographic scope* (df_cleaning_05). We restricted the dataset to trips whose start_city field was tagged 'Lausanne'. This step removed 214 trips (0.35%) and 103 users (1.41%), resulting in 61,721 trips and 7217 users. *Coordinate validity* (df_cleaning_06). We validated the start and end coordinates for numerical range and formatting, ensuring that longitudes fell within [−180, 180] and latitudes within [−90, 90], and that all coordinate pairs in start_longitude, end_longitude, start_latitude, and end_latitude (WGS84) were non-zero. No records were removed at this stage, indicating full syntactic validity of the geospatial fields. Counts therefore remained 61,721 trips and 7217 users. *Identical origin and destination* (df_cleaning_07). We excluded trips whose departure and arrival coordinates were exactly identical, as these records most likely reflect logging artefacts or negligible repositioning events. Removing these cases avoids inflating near-zero distances. This step removed 184 trips (0.30%) and 15 users (0.21%), leaving 61,537 trips and 7202 users. After these seven steps, the trip-level data frame can be confidently converted into a geospatial object suitable for routing. This allows the cleaned dataset to be spatialized (Supplementary Fig. 1) and provides a solid basis for generating network-constrained itineraries for all subsequent modelling stages.

Erroneous OpenTripPlanner bicycle routes (gdf_cleaning_08). We cross-checked all trips against OpenTripPlanner (OTP) routing results and removed those flagged as implausible, such as clearly infeasible. This step excluded 16 trips (0.03%) and 3 users (0.04%). Additional details on the routing procedure are provided in the subsection 'Network-constrained route computation using OpenTripPlanner' (p. 7). *Coordinate and location consistency* (gdf_cleaning_09). We performed a second check to ensure internal consistency across all geospatial fields and verified that each trip was indeed located within the Lausanne agglomeration boundary, even when

start_city was labelled 'Lausanne'. No additional removals were required, leaving 61,521 trips and 7199 users.

Distance outliers (gdf_cleaning_10). We removed rides shorter than 100 m and rides at or above 10,000 m to discard probable GPS noise, stationary events, or mislogged long-distance trips falling outside the system's operational profile^{61,62}. This threshold-based step excluded 1992 trips (3.24%) and 221 users (3.07%). The resulting cleaned analysis dataset, gdf_cleaned_df, contains 59,529 trips and 6978 users, corresponding to net reductions of 5.99% and 5.24%.

Network-constrained route computation using OpenTripPlanner

To obtain realistic distances and travel times, we reconstructed cycling routes between recorded origins and destinations using OpenTripPlanner (OTP). Service-reported distances and durations often reflect GPS imprecision and include non-riding components such as unlocking or parking time. OTP routing allows us to generate geometrically valid shortest-path itineraries constrained by the actual street network, providing a consistent basis for subsequent analyses. OTP was deployed locally and configured exclusively in BICYCLE mode using an OpenStreetMap (OSM) extract of Switzerland. Elevation data were deliberately excluded, as slope effects are largely mitigated by electric assistance in shared e-bike systems. Each trip was routed by submitting origin and destination coordinates to the OTP API. Valid routes were stored as LineString geometries along with routed distance and travel time attributes (Fig. 4). Trips for which routing failed were removed at this stage.

OTP-derived distances and durations were compared with service-reported values. Routed distances were on average 9.05% shorter than reported distances, while routed travel times differed by 1.58%. These discrepancies reflect known GPS and reporting artefacts and confirm that OTP provides a reliable approximation of network-constrained travel behaviour.

Extraction and detection of 'Inside Station Catchment Areas' segments

From the cleaned dataset, we identified trips potentially connected to public transport using a three-step procedure combining spatial, origin–destination, and temporal criteria (Fig. 5).

Identifying trips occurring inside influence areas for DBS rental (gdf_isca_01). The first and most decisive exclusion step consisted of defining pedestrian catchment areas around each station entrance and exit, thereby delimiting the 'socially acceptable' area within which users are willing to walk to access a DBS. This definition relies on a rule-based spatial threshold to identify trips compatible with rail access or egress, operationalised here using buffers of 100 m or 1 min. These spatiotemporal thresholds are consistent with the radius-based sensitivity analysis conducted by Ju et al.⁶³ across four Californian cities, as well as with other empirical studies employing similar parameters³². Our work also builds on the study by Rieder²², which uses a 60-m walking radius around public transport stations to capture dockless bike and e-scooter trips in Zurich, a threshold they identify as the most commonly applied in the literature.

To ensure that this choice does not drive the results, we assess the sensitivity of key ISCA indicators to alternative cutoffs between 50 and 200 m. Figure 6 reports the relative position of several ISCA indicators with respect to DBS benchmarks across thresholds, including peak-hour incidence, proximity to multimodal hubs, and the share of trips below a 2.4 km reference distance (see the subsection 'Spatial and temporal distances', p. 16, for the determination of this threshold). Across this range, these indicators vary only moderately. An auxiliary marginal analysis further shows that trips added when expanding the catchment area beyond this threshold progressively move closer to DBS reference values. We therefore retain this value as the reference threshold in the remainder of the analysis.

As an original contribution of this paper, we further generated isochrones of 1 min walking distance to better reflect the urban reality shaped by physical barriers and potential detours. The resulting isochrones were then merged for each public transport stop. Among the 119,058 origin and destination points projected within the Lausanne metropolitan area, and

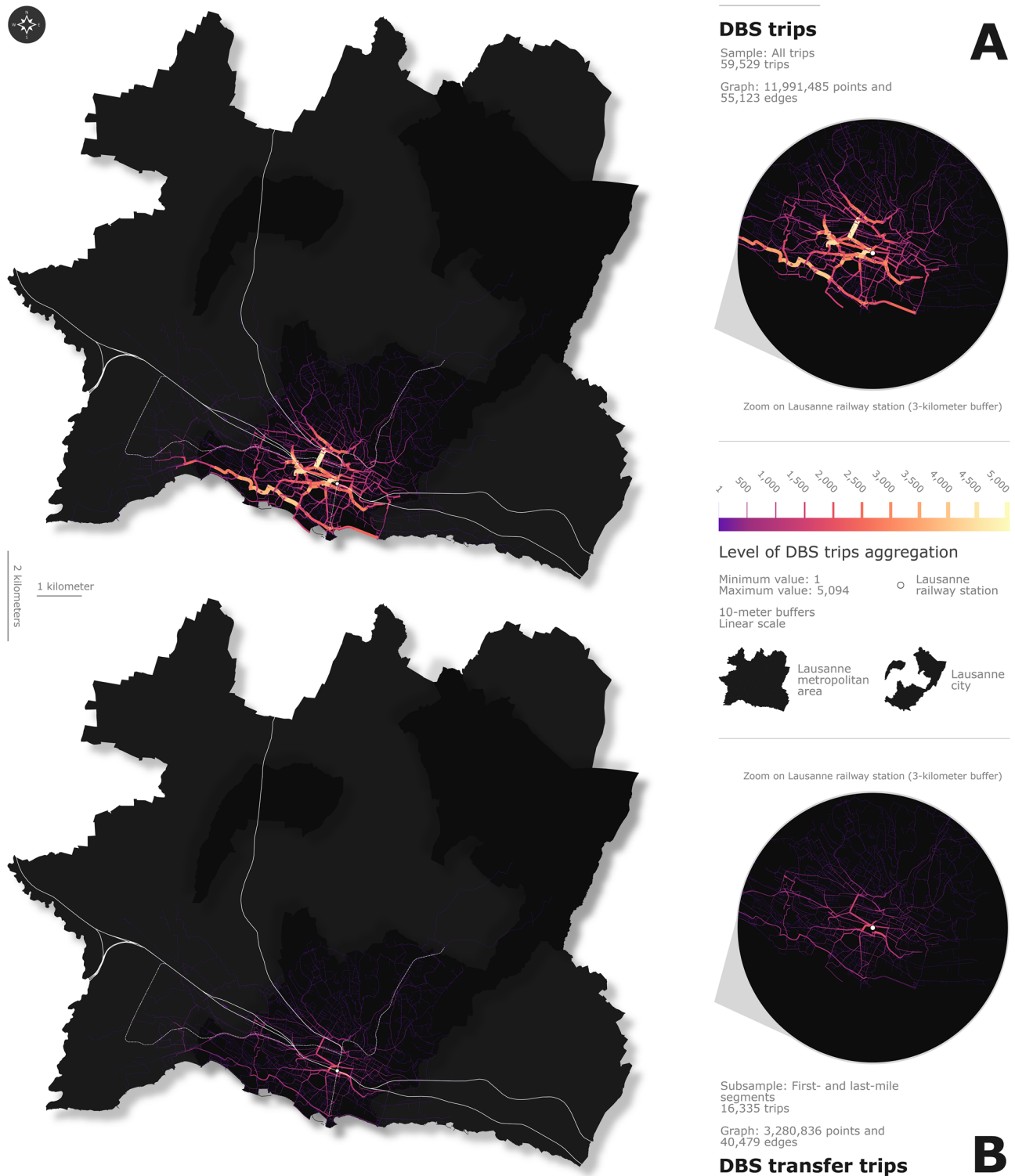


Fig. 4 | Flow map of all cleaned DBS segments across the metropolitan area. Flow map of all cleaned DBS trips and access and egress segments across the Lausanne metropolitan area. The figure displays network-constrained flow maps of routed dockless bikesharing (DBS) trips across the Lausanne metropolitan area, with routes aggregated onto road network edges using 10-m buffers and coloured using a linear scale according to the level of trip aggregation, ranging from dark purple (low aggregation, minimum: 1 trip) through red to light yellow (high aggregation, maximum: 5094 trips).

The dark polygon delineates the Lausanne city boundary. **A** The upper panel shows the full cleaned DBS sample of 59,529 trips, routed on a graph of 11,991,485 points and 55,123 edges. The accompanying circular inset provides a zoomed view within a 3-km buffer around the urban centre station. **B** The lower panel shows the Inside Station Catchment Areas (ISCA) subsample of 16,335 first-mile and last-mile trips, routed on a graph of 3,280,836 points and 40,479 edges. The accompanying circular inset similarly zooms in on the city centre.

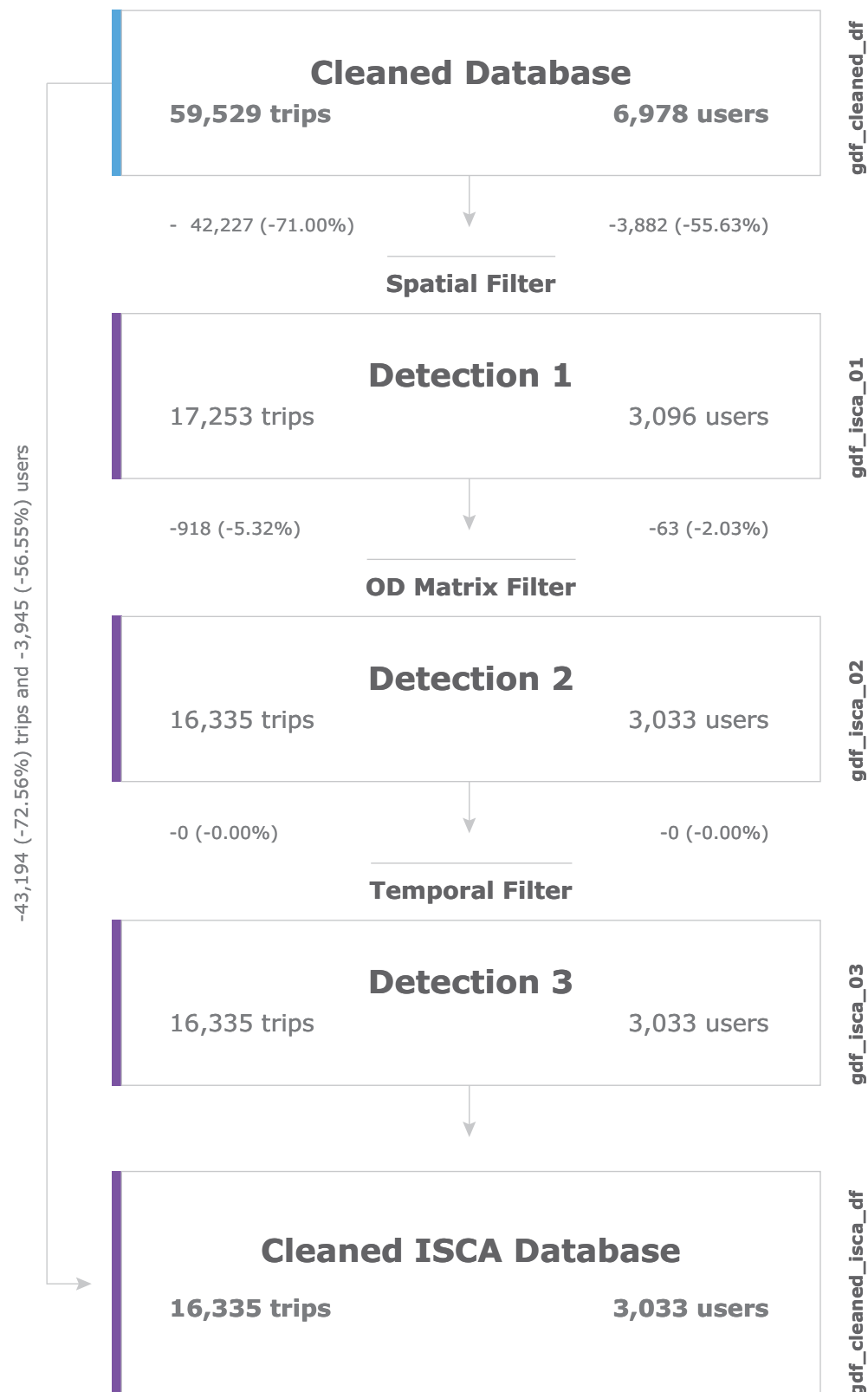


Fig. 5 | Spatiotemporal detection of ‘Inside Station Catchment Areas’ DBS segments (ISCA) within the dataset. The diagram illustrates the three-stage filtering pipeline applied to the cleaned dockless bikesharing (DBS) database to identify trips classified as Inside Station Catchment Areas (ISCA) segments. The input database (`gdf_cleaned_df`) contained 59,529 trips made by 6,978 users. Detection 1 applied a spatial filter retaining only trips whose origin or destination fell within the merged 100-m station catchment areas, reducing the dataset to 17,253 trips and 3,096 users, corresponding to a removal of 42,227 trips (71.00%) and 3,882

users (55.63%). Detection 2 applied an origin–destination matrix filter to ensure that retained trips exhibited a valid intermodal origin–destination pair, resulting in no additional data loss. Detection 3 applied a temporal filter restricting trips to the operational window of train and metro services, removing a further 918 trips (5.32%) and 63 users (2.03%). The final ISCA database (`gdf_cleaned_isca_df`) comprised 16,335 trips made by 3,033 potentially intermodal users, representing an overall reduction of 43,194 trips (72.56%) and 3,945 users (56.55%) relative to the cleaned database.

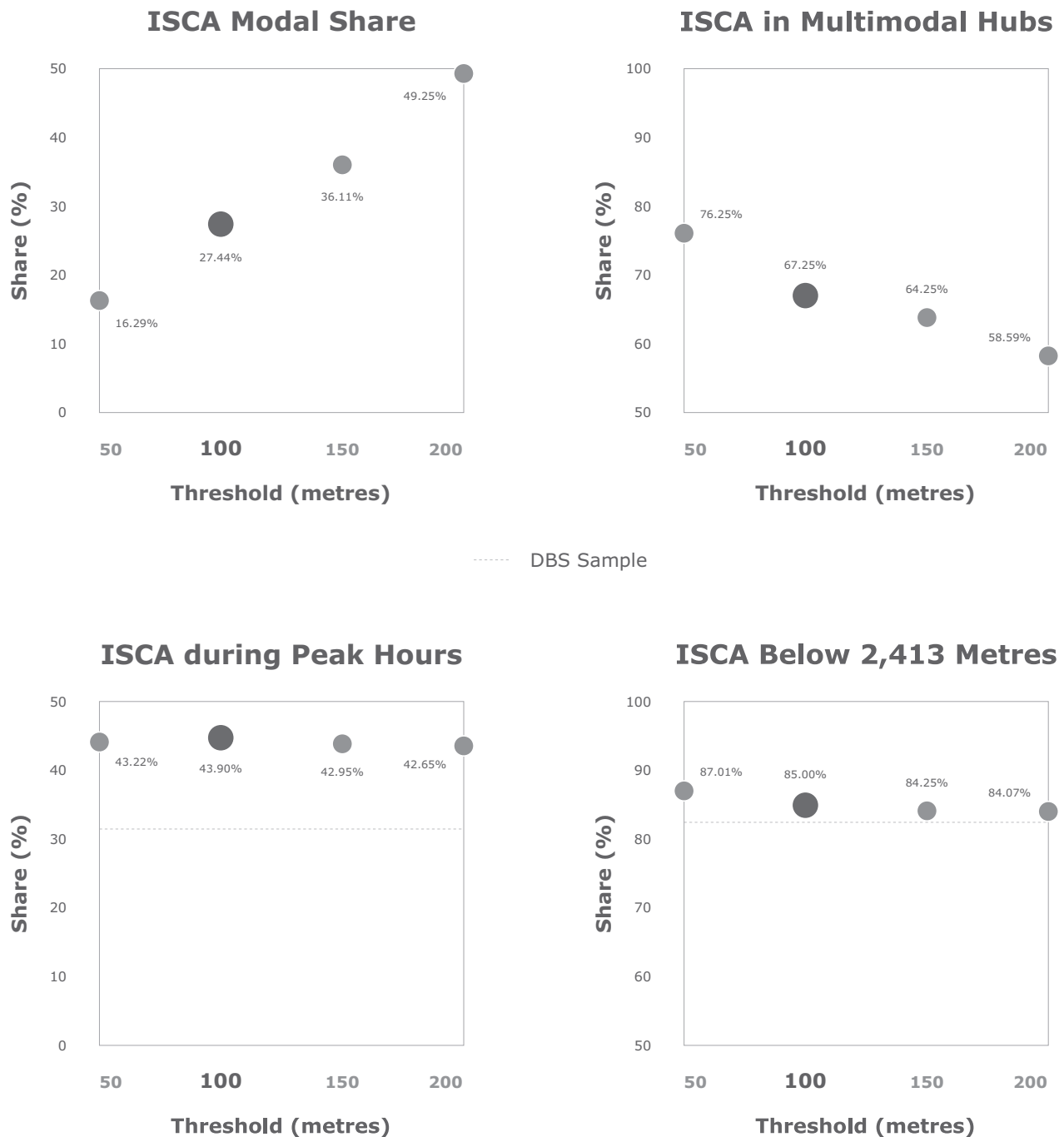


Fig. 6 | Conditional stability of ISCA identification. The four panels display the sensitivity of key Inside Station Catchment Areas (ISCA) characteristics to variations in the spatial proximity threshold, ranging from 50 to 200 m. The reference threshold used in the analysis is 100 m. ISCA modal share (%): The proportion of the cleaned DBS sample classified as ISCA trips increases monotonically with the threshold, from 16.29% at 50 m to 49.25% at 200 m, reflecting the mechanical expansion of the catchment area perimeter. ISCA in multimodal hubs (%): The share of ISCA trips associated with multimodal hubs decreases as the threshold increases, from 76.25% at 50 m to 58.59% at 200 m, suggesting that hub-proximate trips are spatially concentrated close to station entries. ISCA during peak hours (%): The

share of ISCA trips occurring during peak hours remains stable across all thresholds, ranging narrowly between 42.65 and 43.90%, indicating that the temporal composition of detected intermodal trips is robust to the choice of spatial threshold. ISCA below 2413 m (%): The share of ISCA trips with a routed distance below the 2413-m reference value remains stable across thresholds, varying between 84.07 and 87.01%, confirming that the distance distribution of detected trips is insensitive to moderate changes in the spatial criterion. In all panels, the horizontal axis represents the spatial threshold in metres and the vertical axis represents the share in percentage. Annotated values indicate the exact share at each threshold.

given the precision limitations inherent to GPS-based data, we complemented the initial spatial detection (gdf_isca_01) with a spatial point-clustering procedure. The objective was to account for spatial groupings of points in order to compensate for GPS inaccuracies and thus introduce greater spatial tolerance into the detection process. To this end, we applied Hierarchical Density-Based Spatial Clustering of

Applications with Noise (HDBSCAN), an unsupervised clustering algorithm grounded in point density and hierarchical structure, which automatically identifies the most stable e-bike clusters^{64,65}. This step yielded 789 clusters of origin and destination points, which were subsequently overlaid with the merged entrance–exit isochrones of each public transport node (Fig. 7).

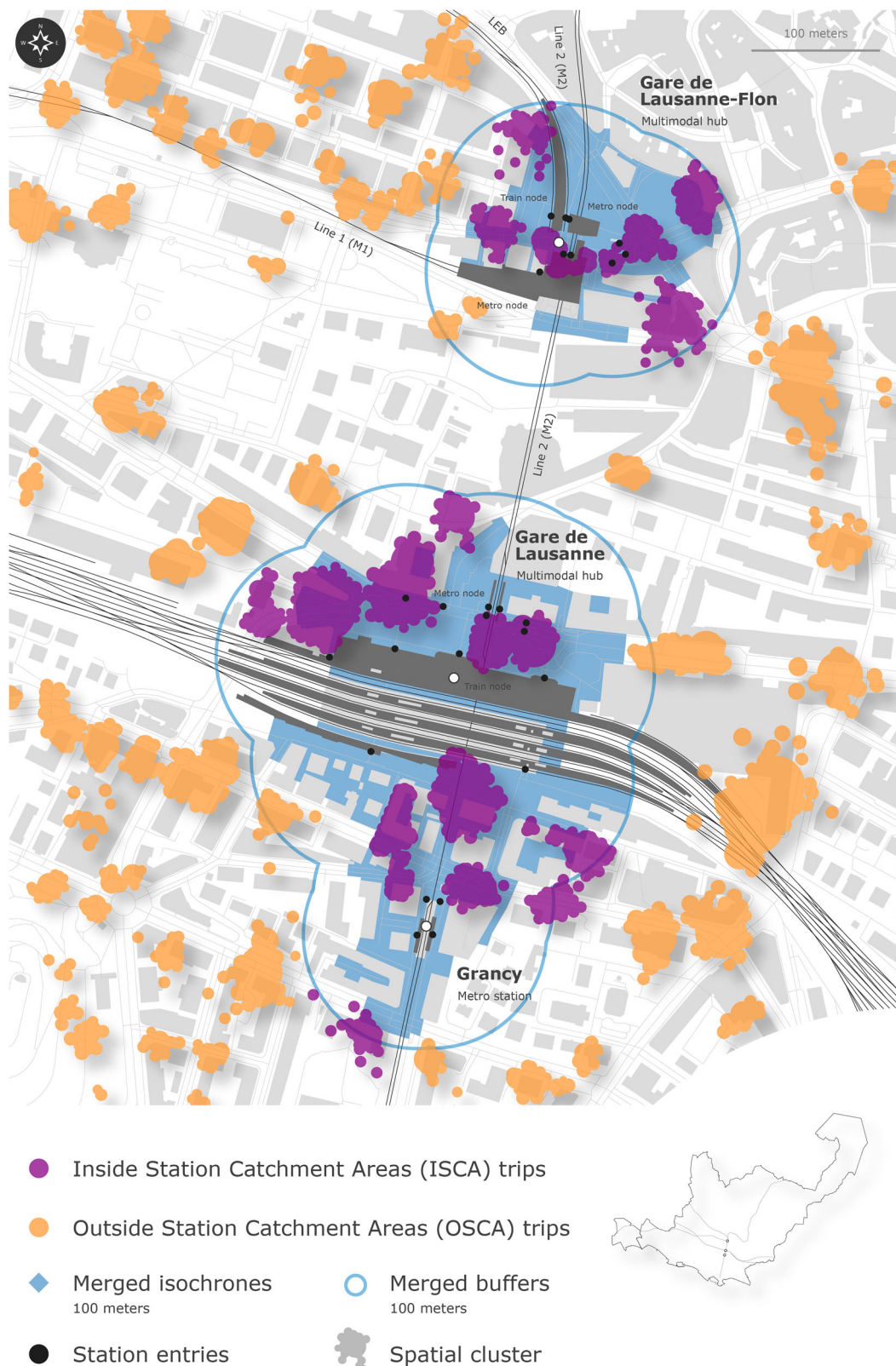
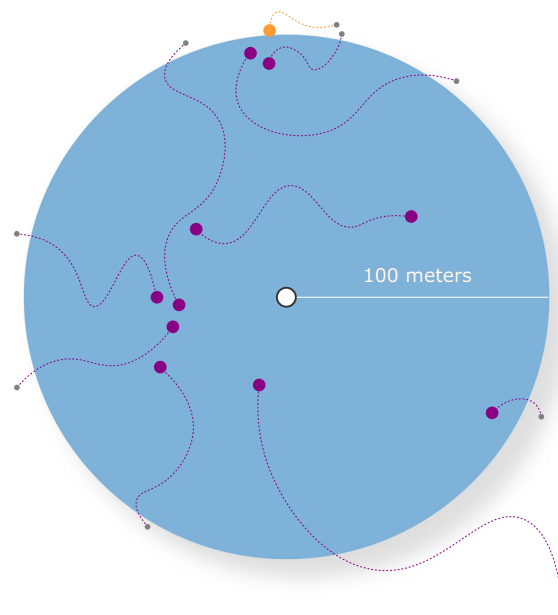


Fig. 7 | Spatial clustering of DBS trips within Gare de Lausanne, Lausanne-Flon, and Grancy 100-m Station Isochrones. The map displays the spatial distribution of dockless bikesharing (DBS) origin or destination points around three transit stations in central Lausanne: Gare de Lausanne-Flon (top, multimodal hub), Gare de Lausanne (centre, multimodal hub), and Grancy (bottom, metro station). Purple-filled circles indicate trips classified as Inside Station Catchment Areas (ISCA) trips, whose points fall within the merged station catchment area. Orange-filled circles

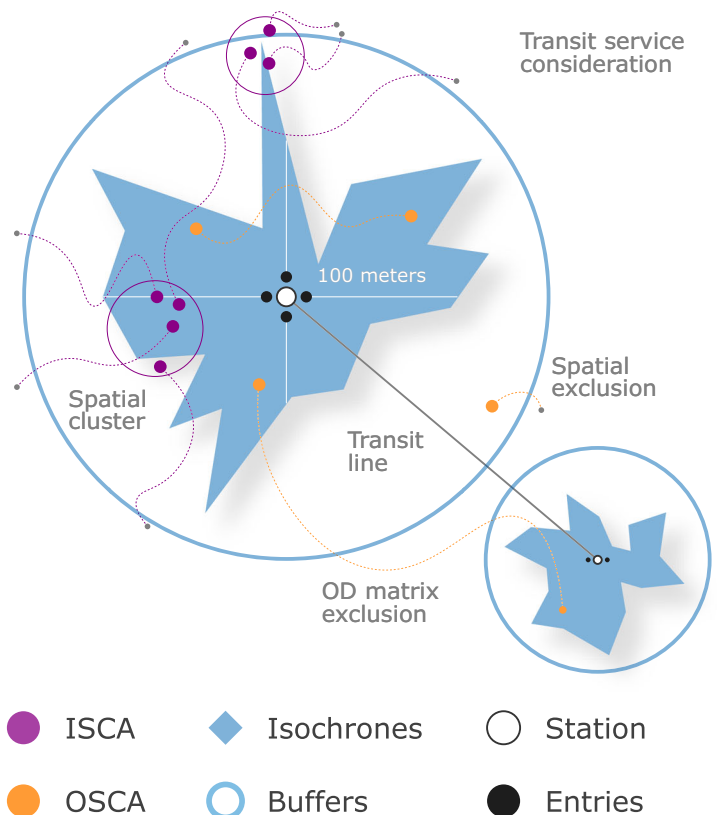
indicate trips classified as Outside Station Catchment Areas (OSCA) trips, which do not meet the spatial proximity criterion. Blue-filled polygons represent merged isochrones of 100 m around each station entry and exit, derived from the pedestrian network. Blue open circles represent merged circular buffers of 100 m. Black-filled circles indicate individual station entry points. Transit infrastructure visible on the map includes Metro Line 2 (M2), Metro Line 1 (M1), and the Lausanne-Échallens-Bercher regional railway (LEB).

Fig. 8 | Advancing bike-and-ride detection through ISCA spatiotemporal filtering. The figure contrasts the conventional bike-and-ride spatial detection approach with the proposed Inside Station Catchment Areas (ISCA) spatiotemporal detection method through two schematic diagrams. The upper panel illustrates the existing bike-and-ride detection approach, which relies solely on a circular buffer of 100 m around a station centroid (large light blue filled circle). DBS points falling within the buffer are indiscriminately classified as intermodal regardless of the actual pedestrian network geometry, transit service availability, or origin–destination logic, resulting in the inclusion of spatially proximate but functionally unrelated trips. The lower panel illustrates our own ISCA spatiotemporal detection method, which combines three successive filters applied within a 100-m perimeter. First, a spatial filter restricts eligible trip points to areas covered by network-derived isochrones (star-shaped light blue filled polygon), which reflect true pedestrian accessibility from station entries rather than a uniform radial buffer (light blue open circle). Second, an origin–destination matrix filter excludes trips whose OD pair does not conform to an intermodal logic. Third, a transit service consideration filter removes trips occurring outside the operational hours of train and metro services. Spatial clusters of retained trip endpoints are indicated by purple open circles. Purple-filled circles indicate ISCA trips, while orange-filled circles indicate OSCA trips.

Existing Bike-and-ride Detection



ISCA Spatiotemporal Detection



From the multiple isochrones generated for each of the 43 stations under study, we retained only those trip origins and destinations located within their boundaries. This spatial exclusion step eliminated 42,277 DBS trips and 3882 unique users, leaving a total of 17,253 trips and 3096 users (Fig. 5).

Adopting a trip-chain logic (gdf_isca_02). The second criterion used to detect ISCA segments rests on the exclusion of trips that, although spatially located within clusters intersecting the walk-accessible

isochrones around rail stations, have both their origin and destination falling within the same observation. In other words, when the start and end points of a shared e-bike trip lie within the same isochrone or within two different isochrones, the trip is excluded as it is highly likely to be non-intermodal and instead to substitute for a metro or train journey. This exclusion criterion did not indicate any such trip in our dataset (Fig. 8). Nevertheless, to the authors' knowledge, this logic has not been applied in

Table 2 | Specification of dependent variables Y

ID	Y	Family	Unit
Usage intensity (Y1, counts, hex100)			
Y1 _{ISCA}	Usage intensity	Poisson	Point (O _{ISCA} , D _{ISCA})
Y1 _{OSCA}			Point (O _{OSCA} , D _{OSCA})
Travel distance (Y2, continuous, points)			
Y2 _{ISCA}	Travel distance	log(distance)	Itinerary (metres)
Y2 _{OSCA}			
Travel time (Y3, continuous, points)			
Y3 _{ISCA}	Travel time	log(time)	Itinerary (minutes)
Y3 _{OSCA}			

previous research and may prove relevant when implemented on larger datasets. *Identifying trips occurring during transit schedules* (gdf_isca_03). A further innovative aspect of this potential bike-and-ride trip extraction method consisted of excluding trips that took place outside the operating hours of the public transport system. For this purpose, we examined the Swiss GTFS data (July 21, 2025), retaining only trips occurring between the first morning departure or arrival and the last evening service. In general, this resulted in a continuous service window between 4 AM and 1 AM. By applying this procedure to all 43 stations, we excluded 918 trips that, although spatially connected to station catchment areas, occurred outside the train and metro service window, an exclusion proportion almost identical to that reported by Ju, Martin, and Shaheen⁶³. This corresponded to 63 fewer users attributable to the temporal criterion (Fig. 5). This final filtering step refines the spatiotemporal detection of ‘Inside Station Catchment Areas’ (ISCA) trips, ultimately yielding a subsample of 16,335 trips made by 3033 potentially intermodal users (Fig. 4B).

Regression models

To address our final research objective, namely, identifying and quantifying the influence of accessibility, built environment, and sociodemographic factors on shared e-bike usage, we estimate a set of regression models on DBS trips classified as ISCA and OSCA (‘Outside Station Catchment Areas’). These include global specifications (GLM and OLS) as well as GWR models estimated across temporal slices, the latter used as a diagnostic tool to assess potential spatial and temporal heterogeneity. The following subsections present the selection of dependent and independent variables, detail the model specification and diagnostic tests, and finally compare the performance of global and local models.

Three dependent variables are considered, capturing complementary dimensions of shared e-bike usage: Usage intensity (Y1), defined as the number of trips per spatial unit, travel distance (Y2), and travel time (Y3). All variables are aggregated on a regular hexagonal grid (hex100) and standardised prior to estimation (Table 2).

Explanatory variables are grouped into three analytical dimensions—accessibility, land use, and sociodemographic characteristics (Table 3)—reflecting complementary determinants of spatial behaviour. Each dimension integrates several thematic categories derived from official statistics and open geodata, allowing us to examine how spatial accessibility, functional land use, and social or material resources are associated with *Bird* mobility behaviours:

- Accessibility (D1), capturing the physical and network-based potential for movement within and towards multimodal nodes, including proximity to stations, road and cycling infrastructure, parking availability, and multimodal services;
- Land use (D2), representing the functional and morphological characteristics of urban space that influence trip generation, destination attractiveness, and activity density;
- Mobility tools and sociodemographic patterns (D3), summarising resident resources, mobility equipment, travel pass ownership, and household attributes that condition modal choice and trip frequency.

Table 3 | Independent variables and associated spatial layers used in the regression models (hex100 and constant across τ)

Aspect	ID	X	Unit	Source
Accessibility (D1)				
Station Proximity (X1)	X1 _A	Distance to nearest entrance	Metres	OSMNx (2025)
	X1 _B	Distance to Lausanne-Flon	Metres	
	X1 _C	Distance to Gare de Lausanne	Metres	
Road Network (X2)	X2 _A	Cycling Paths	Metres	OSM (2025)
	X2 _B	Intersections	Density	OSM (2025)
	X2 _C	Slope	Mean	swissALTI3D (2024)
Parkings (X3)	X3 _A	Cycling Facilities	Capacity	OSM (2025)
	X3 _B	Car Parking Areas	Surface	
Multimodal Services (X4)	X4 _A	BRT and Bus Stops	Sum	GTFS (2025)
	X4 _B	PBS Stations	Sum	OSM (2025)
Land use (D2)				
Population Density	X5	Residents	Density	STATPOP (2024)
Employment Density (X6)	X6 _A	Sector 1	Density	STATENT (2023)
	X6 _B	Sector 2	Density	
	X6 _C	Sector 3	Density	
POIs Density (X7)	X7 _A	‘Local’ POIs	Density	OSM (2025)
	X7 _B	‘Intermediate’ POIs	Density	
	X7 _C	‘Regional’ POIs	Density	
Land Use Types (X8)	X8 _A	Residential	Binary	NOAS04 (2020–2025)
	X8 _B	Public services	Binary	
	X8 _C	Commercial and Office	Binary	
	X8 _D	Industrial	Binary	
	X8 _E	Farmland	Binary	
	X8 _F	Green Space	Binary	
Mobility tool and social factors (D3, weighted)				
Ownership (X9)	X9 _A	Driving Licence	Ratio	MTMC (2021)
	X9 _B	Motorisation	Mean	
	X9 _C	Bicycles	Mean	
	X9 _D	e-Bikes	Mean	
Availability (X10)	X10 _A	Transit Pass	Ratio	MTMC (2021)
	X10 _B	PBS Pass	Ratio	
Demographics (X11)	X11 _A	Age	Mean	MTMC (2021)
	X11 _B	Household Size	Mean	
Resources	X12	Income	Mean	MTMC (2021)

This variable framework builds on existing research, both regarding the components associated with these three analytical dimensions and mobility behaviour more broadly. For instance, Thao and Ohnmacht⁶⁶ draw on Swiss public surveys (STATPOP and MTMC) to examine how densities, POIs, transit accessibility, mobility tools, and sociodemographic attributes influence trip frequency and daily distance travelled across modes. Similarly, Beza, Demissie, and Kattan⁶⁷ investigate the spatiotemporal influence of integrating shared micromobility

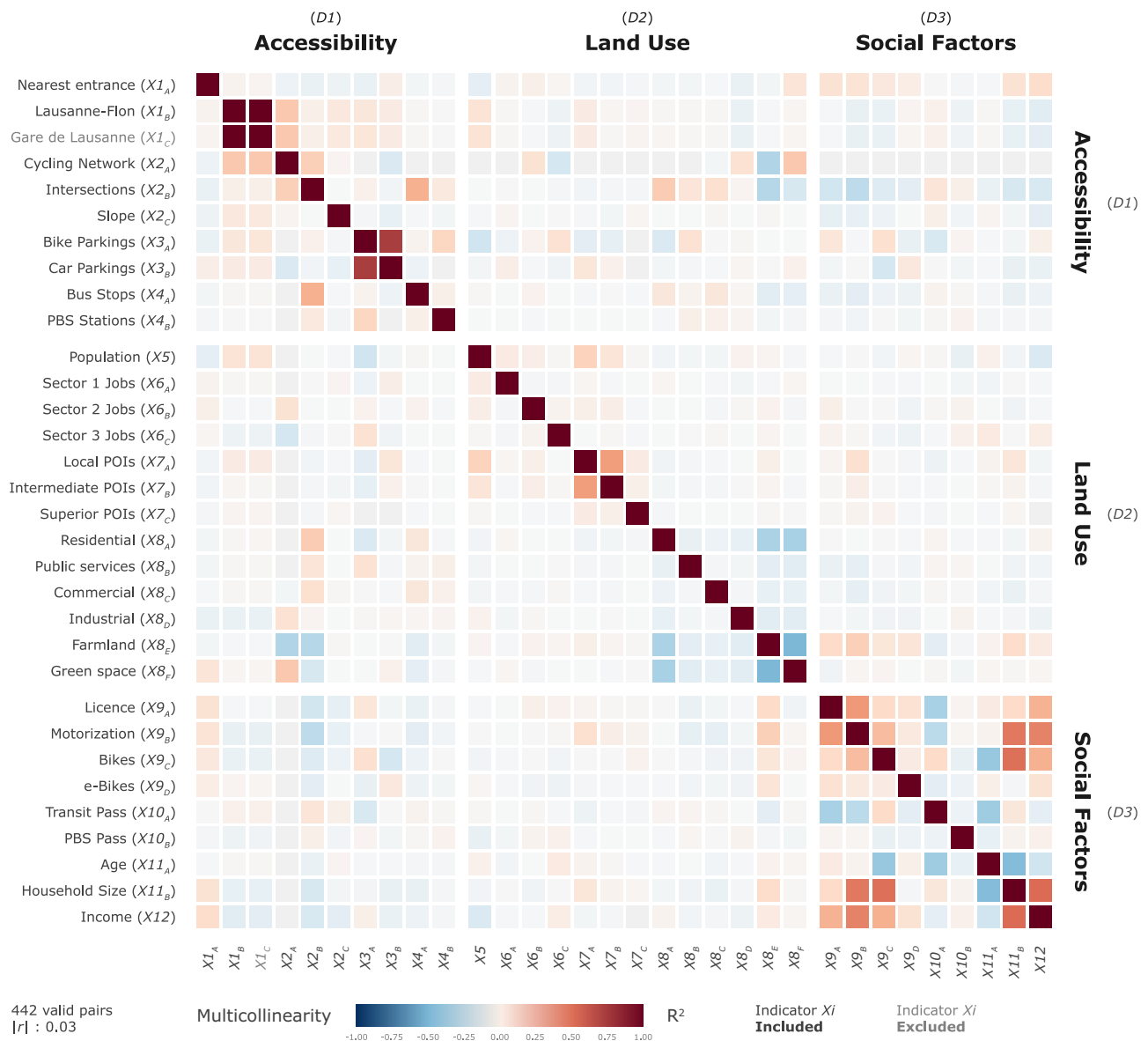


Fig. 9 | Pearson Correlation Matrix among Independent Indicators. The matrix displays pairwise Pearson correlation coefficients (r) between all 33 independent indicators considered in the regression models, grouped into three thematic domains along both axes: Accessibility (D1), Land Use (D2), and Social Factors (D3). Each cell is colour-coded according to the correlation value, ranging from dark blue (strong negative correlation, $r = -1.00$) through white (no correlation, $r = 0.00$) to dark red (strong positive correlation, $r = 1.00$). Indicators retained for inclusion in the models are displayed with coloured cells. Indicators excluded due to multicollinearity are displayed with greyed-out cells. The matrix is based on 442 valid pairs, with a mean absolute correlation of $|r| = 0.03$, indicating

overall low collinearity among retained predictors. Accessibility indicators (D1) include distance to nearest station entrance, distance to Lausanne-Flon, distance to Gare de Lausanne, cycling network density, intersection density, slope, bicycle parking, car parking, bus stops, and public bikesharing stations. Land use indicators (D2) include population, sector 1–3 jobs, local, intermediate, and superior points of interest, and land use classes including residential, public services, commercial, industrial, farmland, and green space. Social factor indicators (D3) include driving licence ownership, motorisation rate, bicycle ownership, e-bike ownership, transit pass, public bikesharing pass, age, household size, and income (X12).

into first- and last-mile public transport journeys. Their regression model incorporates variables related to cycling infrastructure, the built environment, employment, POIs, and social groups. By applying GWR to explore the links between DBS and public transport, Li, Shang, Zhao, and Yang²⁵ rely on the well-established ‘5Ds’, which are also reflected in our indicators. By contrast, Zhang, Cui, Liu, Jia, Shi, and Yu³² extend this framework by integrating additional variables, such as housing prices or metro station passenger volumes, which are not available in our context.

Before estimating the regression models, we performed diagnostic checks to ensure the stability and interpretability of the coefficients. All predictors were standardised to z-scores to facilitate comparability and

avoid scale-dependent effects. We then screened the predictor set for redundant information using pairwise Pearson and Spearman correlations.

Only one pair—distance to Lausanne-Flon ($X1_B$) and to Lausanne-Gare ($X1_C$)—exceeded $|r| > 0.90$, reflecting their close geographic proximity (Fig. 9); these were merged into a single measure of central-station accessibility. Variance Inflation Factors (VIFs) were subsequently computed, with all values remaining well below conventional thresholds (max VIF = 2.65), indicating negligible multicollinearity. These diagnostics confirm that the final predictor set is well-conditioned for regression analysis.

On this basis, we estimate a set of global regression models to quantify the relationships between explanatory variables and shared e-bike usage. For

count outcomes (Y1), we estimate a Poisson GLM, while for continuous outcomes (Y2 and Y3), we estimate global OLS models.

To assess whether these relationships vary across space and time, we complement these global specifications with GWR models estimated across temporal slices. GWR is used here as a diagnostic tool to evaluate the extent of spatial and temporal non-stationarity relative to global models.

Temporal-slice GWR estimation relies on spatial and temporal bandwidths controlling the influence of neighbouring observations. Smaller bandwidths enhance local sensitivity, while larger values yield smoother coefficient surfaces. Model calibration is performed separately for five time periods corresponding to daily peaks, off-peak intervals, and weekends.

Based on the general form of a basic GWR model^{68,69}, we define temporal-slice GWR as follows (Formula (1)):

$$y_i = \beta_0(u_i, v_i, \tau_i) + \sum_k \beta_k(u_i, v_i, \tau_i) x_{ik} + \varepsilon_i. \quad (1)$$

where:

- i is the index of an observation located at (u_i, v_i) and time τ_i
- y_i is the dependent variable at observation i ;
- x_{ik} is the value of the k th independent variable for observation i ;
- $\beta_0(u_i, v_i, \tau_i)$ is the local intercept at (u_i, v_i, τ_i) ;
- $\beta_k(u_i, v_i, \tau_i)$ is the local coefficient of the k th predictor at (u_i, v_i, τ_i) ;
- ε_i is the random error term.

The temporal dimension is discretized into five periods $\tau \in \tau_1, \dots, \tau_5$ corresponding to morning and evening peaks, midday, night, and weekend

Table 4 | Definition of periods τ

ID	Period τ	Time Interval
τ_1	Morning peak (weekdays)	[6:30 AM–9:00 AM]
τ_2	Evening peak (weekdays)	[4:00 PM–7:00 PM]
τ_3	Inter-peak (weekdays)	[9:00 AM–4:00 PM]
τ_4	Off-peak (weekdays)	[7:00 PM–6:30 AM]
τ_5	Weekends	Full day

intervals (Table 4). Bandwidths are selected through cross-validation by minimising the corrected Akaike Information Criterion (AICc) (Supplementary Fig. 3).

We evaluated the performance of global and spatially varying specifications across the three behavioural outcomes (Y1–Y3) and five temporal periods (τ_1 – τ_5), following Hassam, Alpalhão, and Neto⁷⁰ (Table 5).

For Y1, GWR bandwidths ranged from 70 to 100% of active hexagons across periods, indicating convergence toward the global GLM. For Y2 and Y3, bandwidths covered 60–93% and 68–84% of observations, respectively. Although apparent R^2 gains are observed ($\Delta R^2 \approx 0.22$), the magnitude of these bandwidths indicates that improvements reflect broad spatial smoothing rather than locally concentrated heterogeneity.

Temporal comparisons indicate moderate variation in model fit across periods, with slightly higher fit during peak periods for Y1, and during off-peak periods for Y2 and Y3. Residual diagnostics further indicate modest reductions in spatial autocorrelation between global and GWR specifications (Supplementary Fig. 3).

Taken together, these results indicate that spatial non-stationarity remains limited in this context. Global GLM and OLS specifications are therefore retained as the primary analytical framework, while GWR results are reported in the Supplementary Information as a diagnostic and sensitivity analysis (Supplementary Tables 4–6).

Results

This section reports empirical findings on the potential integration of DBS with public transport in the Lausanne metropolitan area. Results are presented following the logic of the proposed framework. Descriptive analyses first establish the magnitude and plausibility of potential intermodal behaviour, accessibility indicators then quantify territorial effects, and regression analyses finally examine the determinants of different dimensions of shared e-bike usage. Throughout, results rely on consistent metrics to enable direct comparisons between ‘Inside Station Catchment Areas’ (ISCA) and ‘Outside Station Catchment Areas’ (OSCA) trips. This subsection establishes the empirical baseline for potential DBS–transit integration by characterising observed mobility behaviours within the ISCA subsample. We compare ISCA and OSCA trips in terms of counts, distance, and travel time, then disaggregate ISCA segments. Access and egress legs are

Table 5 | Model performance comparison between global and local regression models per τ (Y1–Y3)

Model	τ_1		τ_2		τ_3		τ_4		τ_5	
	R^2	AICc	R^2	AICc	R^2	AICc	R^2	AICc	R^2	AICc
Y1										
Global GLM	0.134	3003	0.134	3003	0.134	3003	0.134	3003	0.134	3003
Global GWR	0.299	2945	0.299	2945	0.299	2945	0.299	2945	0.299	2945
GLM per τ	0.093	1546	0.144	1906	0.138	2186	0.136	2036	0.143	2323
GWR per τ	0.128	1551	0.242	1895	0.214	2182	0.173	2044	0.316	2267
Y2										
Global OLS	0.110	3033	0.110	3033	0.110	3033	0.110	3033	0.110	3033
Global GWR	0.319	2883	0.319	2883	0.319	2883	0.319	2883	0.319	2883
OLS per τ	0.062	1565	0.100	1941	0.094	2225	0.146	2028	0.096	2368
GWR per τ	0.236	1524	0.302	1876	0.330	2129	0.453	1881	0.256	2297
Y3										
Global OLS	0.079	3071	0.079	3071	0.079	3071	0.079	3071	0.079	3071
Global GWR	0.286	2935	0.286	2935	0.286	2935	0.286	2935	0.286	2935
OLS per τ	0.078	1555	0.088	1950	0.073	2243	0.103	2064	0.082	2381
GWR per τ	0.296	1506	0.274	1895	0.307	2155	0.395	1926	0.250	2308

Trip count per hexagon (Poisson GLM, pseudo- R^2) for Y1. Median trip distance in metres and duration in seconds (OLS, R^2) for Y2 and Y3. Global models are estimated on all temporal periods pooled ($n = 1092$ active hexagons). Per- τ models are estimated separately on each temporal slice. AICc is directly comparable within each pair sharing the same dataset. Calibrated bandwidths for GWR per τ : Y1 bw/ $n \in [70$ – 100%], Y2 bw/ $n \in [60$ – 93%], Y3 bw/ $n \in [68$ – 84%]. Bisquare adaptive kernel, bandwidth selected by AICc minimisation.

Table 6 | Distribution of transit types and main stations relative to the ISCA and OSCA samples

Transit type	Count	ISCA	Total
Multimodal hubs (4)	10,985	67.25%	18.45%
Gare de Lausanne	7367	45.10%	12.38%
Gare de Lausanne-Flon	1400	8.57%	2.35%
Gare Prilly-Malley	2209	13.52%	3.71%
Gare de Renens VD	9	0.06%	0.02%
Train stations (6)	667	4.08%	1.12%
Metro and LEB stations (33)	4683	28.67%	7.87%
Total (43)	16,335	100.00%	27.44%

Table 7 | Bike-and-ride shares according to different definitions and weighting approaches

Transfer modal shares	Share (%)	OTP (%)
DBS trips		
Trips (count-based)	27.44	–
Access segments	14.12	–
Egress segments	13.32	–
Distance-based	26.41	27.47
Access segments	13.65	13.95
Egress segments	12.76	13.52
Time-based	26.14	27.93
Access segments	13.45	14.42
Egress segments	12.69	13.51
DBS users		
User adoption (at least one combined trip)	43.47	–
User-weighted (by number of trips)	25.92	–
Within intermodal users	59.64	–

analysed separately to assess their respective contributions, and spatio-temporal effort distributions are used to identify typical transfer profiles.

Overall ISCA modal split

ISCA trips involving rail account for 27.44% of all recorded DBS trips. Given a 10% margin of error, reflecting the assumption in the literature that around 90% of DBS stops near stations correspond to public transport access⁶³, it is therefore reasonable to infer that approximately 24.70% of DBS riders in Lausanne start or end their trip close to a rail station. When weighted by travel distance, the ISCA share reaches 26.41% in the cleaned database. For travel time, ISCA trips represent 26.14% of total observed duration (Table 7). Disaggregating by public transport network type, hubs capture the largest share of ISCA itineraries. The four multimodal hubs account for 67.25% of all ISCA trips and 18.45% of total DBS trips (Table 6). Gare de Lausanne alone concentrates 45.10% of ISCA transfers, corresponding to 12.38% of the full DBS sample.

At the user level, 43.47% of individuals undertook at least one ISCA trip. When weighting users by their number of trips, the intermodal share decreases to 25.92%, suggesting that a smaller group of frequent travellers accounts for a disproportionate share of potential bike-and-ride movements. Among ISCA users, ISCA trips represent, on average, 59.64% of their personal activity, indicating that once adopted, potential bike-and-ride becomes a central and recurring component of individual mobility patterns (Table 7).

The distribution of ISCA trips between access and egress segments is balanced (Supplementary Fig. 4). Access segments account for 51.45%

of potential transfer trips, while egress segments represent 48.55%. When weighted by distance, access shares reach 51.70% and egress 48.30% (Table 7). To capture combined behaviours, we identified ISCA users who relied on the service both to reach and to leave a station on the same day (paired access–egress segments). In total, 345 users engaged at least once in this symmetrical modal combination, yielding 874 paired trips. This corresponds to 11.1% of ISCA users and 5.1% of trips in the potential bike-and-ride subsample. Notably, 36.7% of these pairs occurred during peak hours, suggesting that they mainly correspond to commuting journeys.

Temporal variations and trip purposes

We next characterise the temporal structure of DBS–transit integration by computing ISCA modal shares by day of week and hour of day. ISCA segments display a moderately commuter-oriented profile (Fig. 10). On weekdays, the ISCA share reaches 28.2%, compared with 25.5% on weekends. Over the diurnal cycle, ISCA behaviour shows a marked midday trough (around 25% between 10 AM and 3 PM), consistent with a higher prevalence of short, all-bike trips around lunchtime. Early-morning and late-evening shares are comparatively higher (around 31% at 05–06 AM and 10–11 PM), although low volumes warrant cautious interpretation (Fig. 11). In volume terms, ISCA activity is most concentrated between 3 PM and 6 PM (Supplementary Fig. 4).

The temporal distribution of access and egress segments mirrors home-based commuting rhythms. For access trips, 20.7% occur during the morning peak and 23.9% during the evening peak. Egress trips account for 10.7% of morning-peak activity but 29.7% of evening-peak activity. Nearly half of all ISCA trips thus take place during peak hours, indicating that potential intermodal cycling is primarily embedded within commuting routines, with access trips supporting the morning rush and egress trips disproportionately shaping evening returns.

Spatial and temporal distances

These temporal variations frame the analysis of the spatial and temporal extent of ISCA transfers. The 16,335 potential intermodal segments are strongly concentrated around short cycling distances and durations. Access and egress legs display a nearly identical median length of around 1.4 km, corresponding to roughly 7 min of travel (Table 8). Median distance–time pairs correspond to cycling speeds of 11–13 km/h, consistent with typical observed cycling speeds. Access and egress segments share the same median distance (Fig. 12), but access trips exhibit a larger standard deviation, indicating greater variability and a non-negligible share of longer access segments. Egress trips appear more homogeneous, with fewer extreme values.

We relied on a commonly used threshold to measure the distance considered ‘socially acceptable’ for transfer segments³⁰: The 85th percentile of the cumulative distribution of cycling distances¹⁰. In integrated bicycle use, this percentile is commonly interpreted as an acceptability benchmark for access to public transport^{71–75}. Here, the 85th percentile corresponds to 2.4 km or 12 min for FLM connections, delineating the empirical influence area of station neighbourhoods¹⁰. Given that the acceptable walking distance in the canton of Vaud is estimated at 1.0 km from MTMC 2015 analyses³⁹, station areas extended by DBS can be considered theoretically 5.8 times larger in surface area than those reachable on foot, corresponding to an absolute difference of 1500 ha (15 km²) per buffer. Considering origin–destination pairs, their potential combinations expand multiplicatively, and extended station catchments theoretically enable users to reach up to 33.2 times more locations. However, theoretical coverage is not sufficient to capture the capacity of DBS to expand station catchments and systemic accessibility. The next subsection, therefore, examines regional accessibility gains in terms of populations and destinations that become reachable through these services^{76–79}. This subsection quantifies territorial accessibility gains produced by integrating DBS with the public transport network. Using empirically derived spatial and temporal thresholds, it assesses the extent

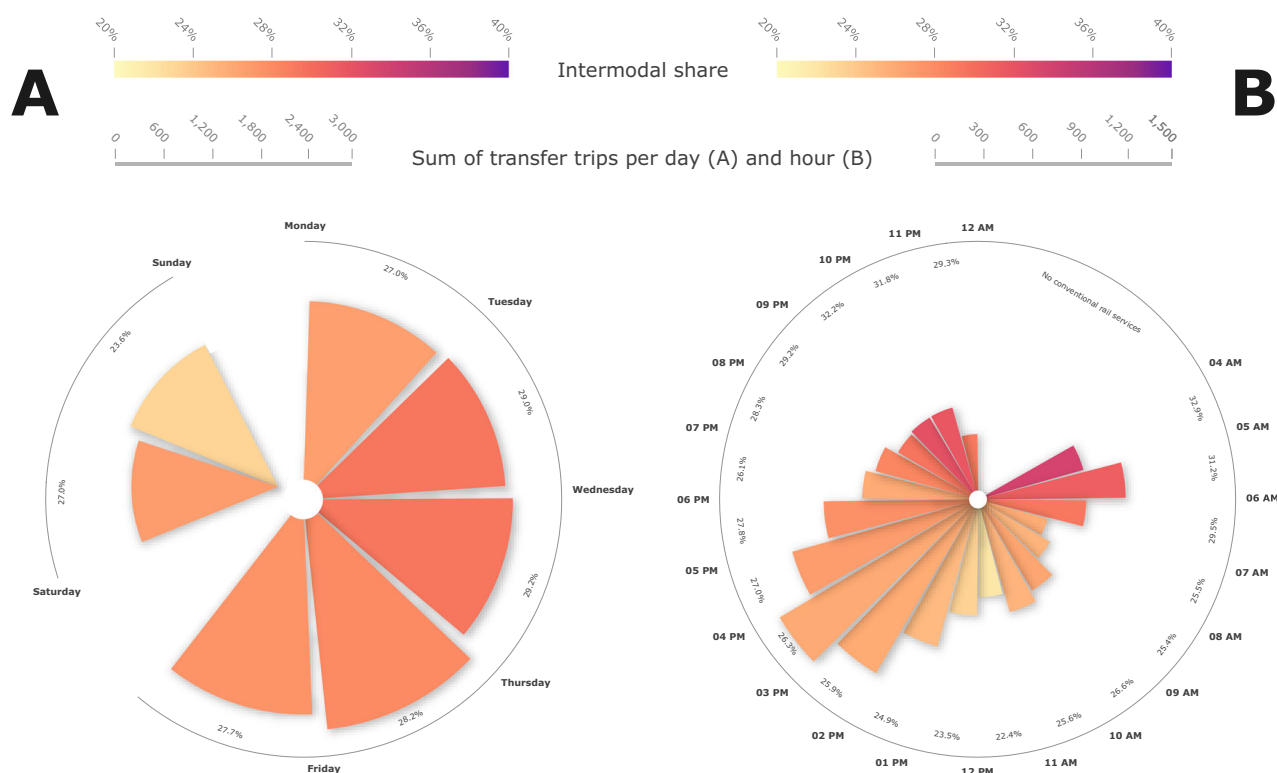


Fig. 10 | Hourly and weekly variations in access and egress DBS transfers. Two polar charts display the temporal distribution of dockless bikesharing (DBS) classified as Inside Station Catchment Areas (ISCA) trips, with sector colour indicating the ISCA share, ranging from light yellow (low share, approximately 20%) to dark purple (high share, approximately 40%). **A** The weekly radar chart displays one sector per day of the week, with the ISCA share annotated for each day. Weekdays exhibit higher ISCA shares, peaking on Wednesday (29.2%) and Thursday (28.2%), while Sunday records the lowest share (23.6%), consistent with more leisure-

oriented travel on weekends. Saturday (27.0%) and Monday (27.0%) show intermediate values. **B** The hourly radar chart displays one sector per hour of the day from 04:00 to 12:00 midnight. ISCA shares are at their highest during the early morning hours (04:00–06:00 AM, reaching 32.9 and 31.2% respectively) and remain moderately elevated during the evening hours (09:00–10:00 PM, 31.8–32.2%). Mid-morning and early afternoon hours (10:00 AM–02:00 PM) record the lowest intermodal shares, between 22.4 and 25.9%. Sector radius reflects the total sum of transfer trips per day (panel a, scale 0–3000) and per hour (panel b, scale 0–1500).

to which DBS enlarges station catchment areas beyond walking isochrones in terms of surface coverage, network accessibility, population and employment coverage, and destination accessibility.

Expanded spatial coverage and accessibility gains

We assess the effective surface area reachable through the spatial extension of station catchments enabled by DBS, assuming the service operates across the entire study perimeter (132.6 km²). One-km walking isochrones cover 17.3% of the metropolitan area (22.8 km²). With DBS, coverage expands to 44.2% (58.1 km²), representing a 2.6-fold increase in catchment area. Street-network accessibility shows a similar pattern (Fig. 13A). In the walk-and-ride scenario, 54.5% of street segments fall within station catchment areas, representing 41.2% of total network length. With DBS, coverage rises to 84.4% of segments and 73.1% of total length, equivalent to 1.5 times more accessible segments and 1.8 times greater accessible network length.

Combining isochrones with built environment data (Fig. 13B) shows that walking-only conditions place 42.1% of buildings, accounting for 40.8% of total gross floor area (GFA), within accessible zones. Including DBS raises these shares to 76.0% of buildings and 80.4% of GFA, corresponding to 1.8 times more accessible buildings and a twofold increase in accessible floor space. In terms of accessibility by population (BBTOT), walking isochrones already include 69.8% of metropolitan residents ($n = 213,766$). Extending access through DBS raises potential coverage to 93.0% ($n = 284,853$), a 1.3-fold increase. Population densities remain higher in walking isochrones ($n = 5839$ inhabitants/km²) than in DBS-accessible areas ($n = 3989$ inhabitants/km²), indicating that expanded catchments are on average 1.5 times less dense. Accessibility gains must also be interpreted through access to employment and activity locations, structuring daily mobility⁸⁰. For total

employment (B08EMPT), extending station catchments through DBS increases accessible jobs by a factor of 1.3: Walking isochrones cover 73.9% ($n = 171,947$), whereas cycling isochrones reach 95.1% ($n = 221,103$). By sector, accessibility gains range from 1.25 to 1.77. Primary sector coverage (B08EMPTS1) increases from 41.5% ($n = 308$ jobs) to 65.0% ($n = 483$ jobs). Secondary sector coverage (B08EMPTS2) rises from 51.5% ($n = 12,984$ jobs) to 90.9% ($n = 22,931$ jobs). Tertiary sector coverage (B08EMPTS3) improves from 76.7% ($n = 159,820$ jobs) to 95.7% ($n = 199,350$ jobs). Beyond employment, we assess destination opportunities using POIs (osm_pois). Walking isochrones provide access to 74.7% of POIs ($n = 1872$), whereas integrating DBS raises this share to 94.8% ($n = 2376$), a 30-percentage-point improvement with similar relative gains across categories. Disaggregating by POI category (fclass) shows that DBS makes approximately 1.3 times more POIs of every type accessible. For 'regional' POIs, 100.0% ($n = 24$) are reached, compared with 83.3% ($n = 20$) under walking conditions. For 'intermediate' POIs, coverage increases from 72.2% ($n = 179$) to 95.2% ($n = 236$). For 'local' POIs, 94.7% ($n = 2116$) become accessible, compared with 74.9% ($n = 1673$) in the walk-and-ride case. This final subsection examines how ISCA and OSCA behaviours relate to their underlying determinants through global regression models. Whereas previous sections characterised the magnitude and territorial reach of potential DBS–rail integration, this analysis identifies the accessibility, built environment, land use, and sociodemographic factors associated with different dimensions of shared e-bike behaviour at the metropolitan scale.

Table 9 reports statistically significant standardised coefficients from the global GLM (Y1) and OLS (Y2 and Y3) models, estimated separately for ISCA and OSCA trips. Results reveal both common structural determinants and notable differences between the two groups, with several variables

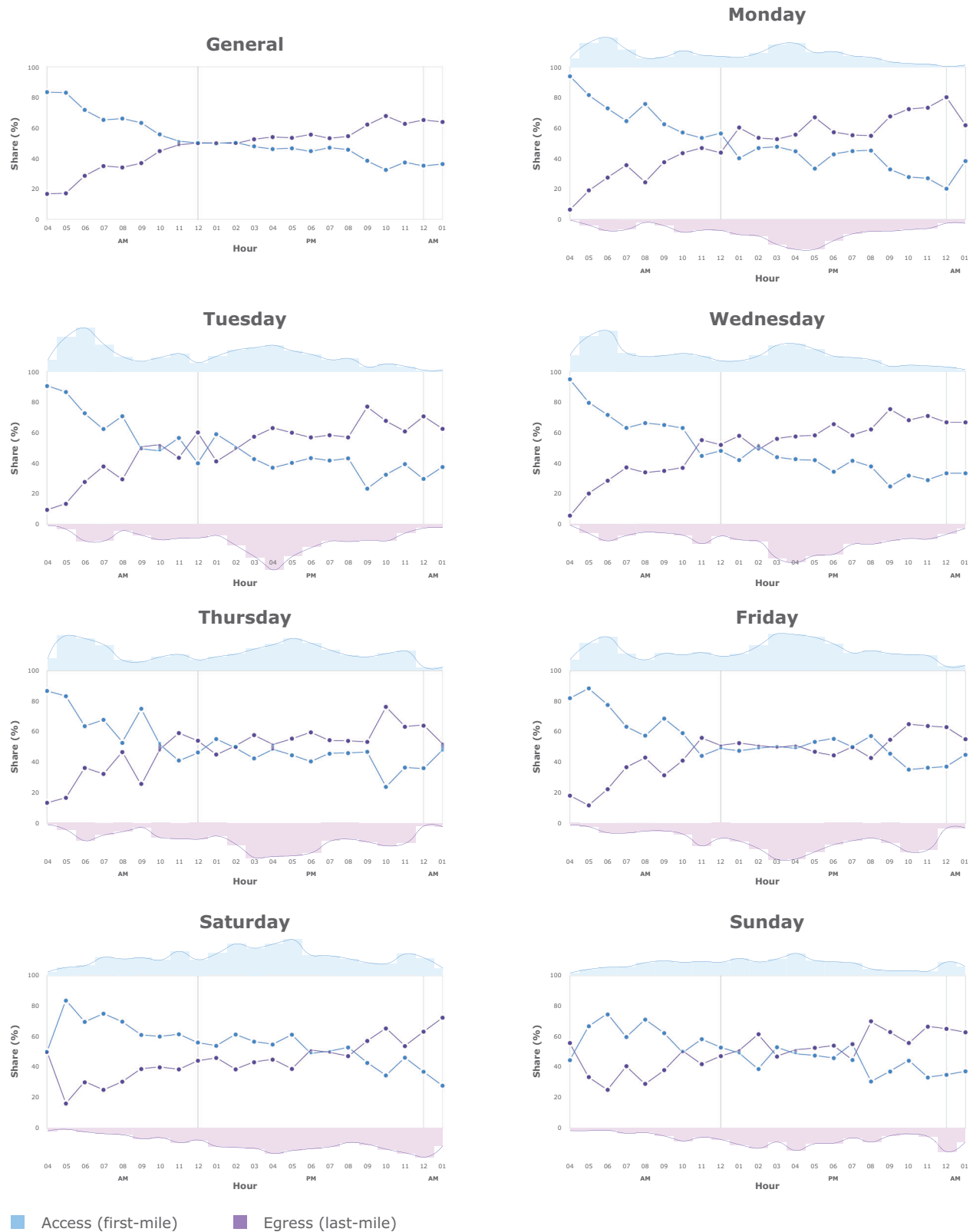


Fig. 11 | Temporal asymmetry between access and egress DBS segments. For each panel, the horizontal axis represents the hour of the day and the vertical axis represents the share (%) of ISCA trips. Across weekdays, access trips dominate the AM period, reflecting outbound commuters cycling to transit stations, while egress trips gain share throughout the PM period, consistent with return commuting.

Weekend panels exhibit a more balanced and less temporally structured distribution between potential access and egress shares. The light blue line indicates access (first-mile) ISCA trips, the purple line indicates egress (last-mile) ISCA trips, and filled circles mark hourly observed values.

Table 8 | Descriptive statistics of access and egress transfer trips in spatial distance and duration

Summary measure	Kilometres	Minutes
Overall (count: 16,335)		
Mean	1.61	7.85
Standard deviation	0.95	4.29
Minimum value	0.10	0.40
Q1	1.03	5.02
Median	1.40	7.00
Q3	1.99	9.95
Maximum value	8.56	38.13
P85	2.42	11.77
Access legs (count: 8405)		
Mean	1.59	7.78
Standard deviation	0.96	4.39
Minimum value	0.10	0.40
Q1	1.01	4.93
Median	1.39	6.95
Q3	2.01	10.07
Maximum value	8.56	38.13
P85	2.43	11.83
Egress legs (count: 7930)		
Mean	1.63	7.93
Standard deviation	0.94	4.17
Minimum value	0.10	0.40
Q1	1.04	5.10
Median	1.41	7.03
Q3	1.96	9.85
Maximum value	7.69	37.00
P85	2.39	11.68

exhibiting contrasting signs or magnitudes, suggesting that factors associated with potential intermodal behaviour differ from those shaping unimodal DBS use.

Determinants of usage intensity

For usage intensity (Y1), the most pronounced effects are observed among accessibility variables, followed by land use and sociodemographic factors, with systematic differences between ISCA and OSCA behaviours.

Among accessibility indicators, the presence of PBS bikesharing stations (X4_B) is one of the strongest positive predictors of ISCA intensity ($\hat{\beta}_{ISCA} = 0.305^{***}$), while its effect remains negligible for OSCA ($\hat{\beta}_{OSCA} = 0.009^*$). This suggests that shared mobility infrastructure plays a central role in supporting potential bike-and-ride activity.

In contrast, BRT and bus stop density (X4_A) exhibits opposite effects across the two groups ($\hat{\beta}_{ISCA} = -0.140^{***}$, $\hat{\beta}_{OSCA} = 0.120^{***}$). Areas well served by bus networks tend to generate autonomous DBS use, while reducing the likelihood of rail-oriented intermodal combinations.

Street network characteristics display consistent effects. Intersection density (X2_B) is positively associated with both ISCA and OSCA intensity, with a stronger effect for ISCA ($\hat{\beta}_{ISCA} = 0.230^{***}$ vs 0.114^{***}), indicating that well-connected networks facilitate station access. Slope (X2_C) is negatively associated with both groups, more strongly for ISCA (-0.273^{***}), confirming that topography remains a constraint even for e-bikes. Cycling facilities (X3_A) are positively associated with both groups, reflecting the importance of local infrastructure.

Land use variables show more contrasted patterns. Residential areas (X8_A) are negatively associated with both ISCA and OSCA intensity, with a

stronger effect for ISCA (-0.322^{***} vs -0.130^{***}), suggesting that residential zones generate fewer rail-oriented cycling trips.

Farmland (X8_E) and green space (X8_F) exhibit opposite patterns between ISCA and OSCA: They are negatively associated with ISCA intensity (-0.169^{***} and -0.191^{***}), but positively associated with OSCA (0.029^{***} and 0.038^{***}), indicating that periurban environments support autonomous cycling but are less conducive to intermodal use.

Employment in primary and secondary sectors (X6_A and X6_B) is negatively associated with both groups, while regional POIs (X7_C) are positively associated with both, reflecting the role of central destinations in structuring demand.

Sociodemographic and mobility-tool variables display the clearest divergence between ISCA and OSCA behaviours. Driving licence prevalence (X9_A) is positively associated with ISCA intensity (0.224^{***}) but negatively associated with OSCA (-0.093^{***}), suggesting that populations with access to multiple transport options are more likely to combine DBS with rail.

Age (X11_A) is strongly negatively associated with ISCA (-0.245^{***}) but only weakly with OSCA, indicating that younger populations are more likely to engage in intermodal cycling. Transit pass ownership (X10_A) is positively associated with ISCA only (0.133^{***}), reinforcing the link between public transport use and DBS integration.

Determinants of travel distance and duration

Results for median trip distance (Y2) and duration (Y3) are presented jointly, given the strong correlation between the two outcomes and their largely overlapping determinants.

Compared to usage intensity, fewer variables are significant, and effect sizes are smaller, indicating that once DBS trips occur, their spatial and temporal extent is less strongly structured by the built environment.

The most consistent predictor across both outcomes is income (X12), which is negatively associated with ISCA trip distance and duration ($\hat{\beta}_{ISCA} = -0.197^{***}$ for Y2 and -0.215^{***} for Y3), and more weakly for OSCA. Higher-income areas are therefore associated with shorter intermodal trips.

Age (X11_A) is positively associated with both distance and duration for ISCA, suggesting that older users tend to perform slightly longer trips, while effects remain weaker for OSCA.

Local POI density (X7_A) is positively associated with both distance and duration, indicating that destination-rich environments generate longer or more complex trips.

Overall, these results suggest that while usage intensity is strongly shaped by accessibility and land use conditions, trip distance and duration are more weakly structured and primarily associated with individual socioeconomic context and local destination density.

Temporal modulation of determinants

While the global regression models capture the dominant and globally consistent associations between contextual factors and DBS behaviour, estimating the models separately for each temporal slice provides additional insights into how these relationships vary across periods (Supplementary Tables 1–3). These variations should be interpreted as indicative patterns rather than strong evidence of localised heterogeneity. The two strongest predictors of ISCA intensity both display a clear temporal gradient consistent with commuting patterns. PBS station presence (X4_B) shows its highest association during the morning and evening peaks ($\hat{\beta}_{\tau_1} = 0.426^{***}$, $\hat{\beta}_{\tau_2} = 0.408^{***}$), with lower values observed during weekends ($\hat{\beta}_{\tau_5} = 0.263^{***}$). Transit pass ownership (X10_A) follows a similar pattern, decreasing from $\hat{\beta}_{\tau_1} = 0.267^{***}$ to $\hat{\beta}_{\tau_5} = 0.081^{***}$. These results suggest that the integration of DBS with rail is more strongly associated with commuting periods than with off-peak or leisure contexts. The negative association between bus stop density (X4_A) and ISCA intensity is also more pronounced during the morning peak ($\hat{\beta}_{\tau_1} = -0.407^{***}$) and weakens across the day, becoming relatively small on weekends ($\hat{\beta}_{\tau_5} = -0.068^{***}$). For OSCA trips, the association becomes positive from τ_2 onward

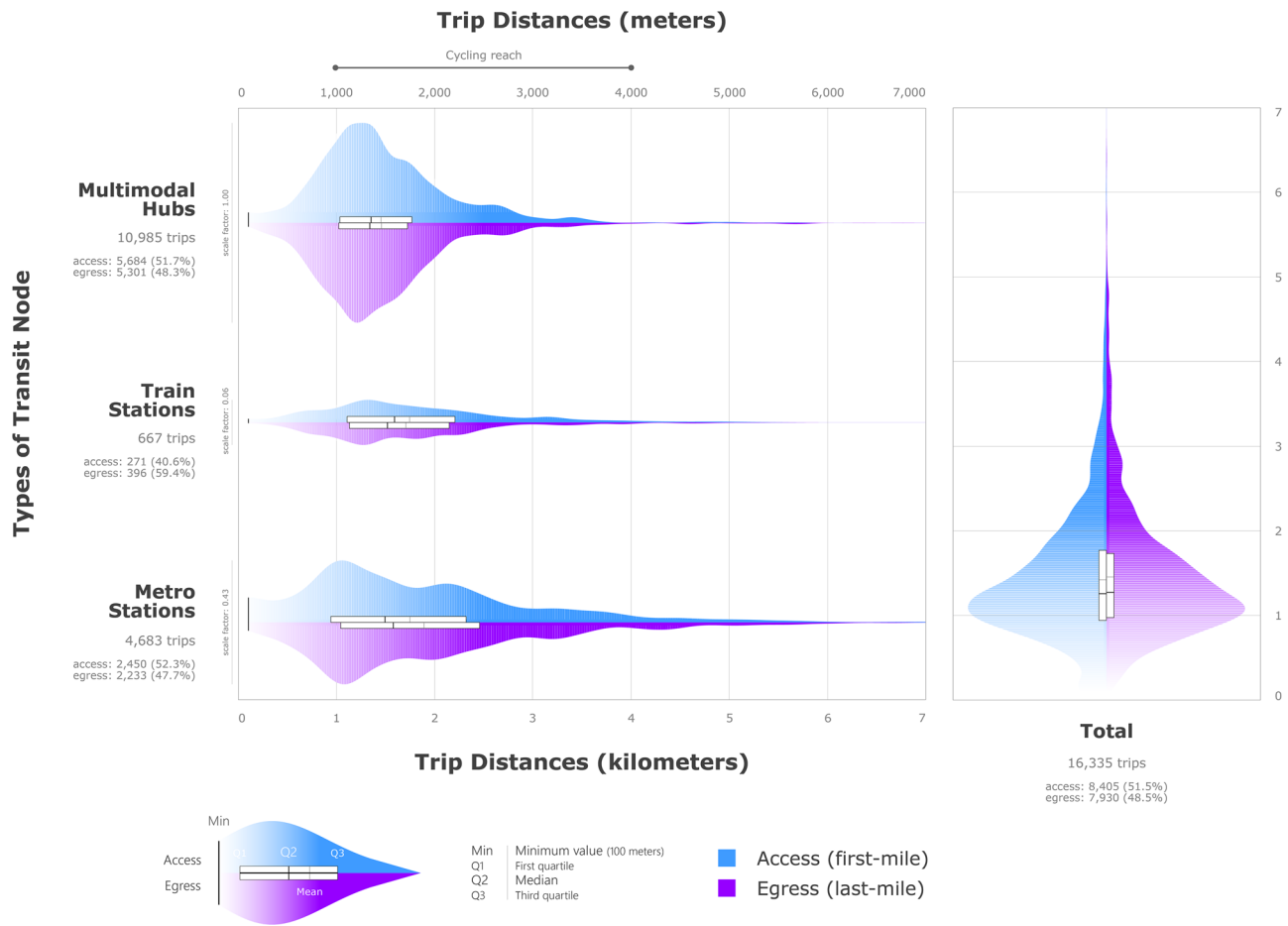


Fig. 12 | Violin plots of access and egress distances travelled by intermodal riders using DBS. The figure displays mirrored violin plots of routed Inside Station Catchment Areas (ISCA) trip distances (in metres, bottom axis and in kilometres, top axis) for access (first-mile, upper half, blue) and egress (last-mile, lower half, purple) segments, stratified by transit node type across four columns: Total (16,335 trips), Multimodal Hubs (10,985 trips), Metro Stations (4,683 trips), and Train Stations (667 trips). Violin widths are scaled relative to the total column (scale factors: Total: 1.00,

Multimodal Hubs: 0.43, Metro Stations: 0.43, Train Stations: 0.06). Within each violin, horizontal lines indicate the first quartile (Q1), the median (Q2), and the third quartile (Q3). Across all node types, access and egress distance distributions are broadly similar, with access segments accounting for 51.5% and egress for 48.5% of total ISCA trips. Multimodal hubs concentrate the largest share of trips (67.2%), with a near-equal access–egress split (51.7–48.3%). Train stations show a higher egress share (59.4%). Metro stations show a slight access dominance (52.3–47.7%).

($\hat{\beta}_{\tau_2} = 0.112^{***}$), suggesting that proximity to bus networks is more closely related to independent cycling activity outside intermodal contexts. Commercial and office land use (X_{8C}) exhibits a change in association across periods for ISCA trips. It is positively associated during the evening peak ($\hat{\beta}_{\tau_2} = 0.084^{***}$) but becomes negative during off-peak and weekend periods ($\hat{\beta}_{\tau_4} = -0.061^{***}$ and $\hat{\beta}_{\tau_5} = -0.076^{***}$). This pattern is consistent with employment areas acting as destinations in evening egress trips, while playing a more limited role outside commuting periods. Income (X_{12}) also shows variation across periods for ISCA intensity. It is positively associated during the morning peak ($\hat{\beta}_{\tau_1} = 0.252^{***}$) and becomes negative during inter-peak and evening periods ($\hat{\beta}_{\tau_3} = -0.119^{***}$). For OSCA trips, income remains positively associated throughout the day. This contrast may reflect differences in mobility patterns across income groups depending on time of day, particularly in relation to commuting structures.

Discussion

This study examined the potential integration of DBS with public transport in the Lausanne metropolitan area using a full year of operator-provided trip data. By combining network-based routing and a spatiotemporal identification framework, we identified behavioural, accessibility, and environmental patterns shaping potential intermodal practices. The findings demonstrate that DBS contributes meaningfully to FLM connectivity and can substantially extend the effective catchment areas of regional rail

systems. While the analysis focuses on potential rather than confirmed transfers, the observed magnitudes, spatial structures, and determinants provide a robust basis for assessing the role of shared micromobility in multimodal sustainability. Taken together, the contribution of this paper lies in the articulation between identification, measurement, and explanation of potential intermodal practices.

The analysis indicates that approximately one in four DBS trips in the Lausanne metropolitan area occurs within the spatial and temporal influence of a rail station. This magnitude aligns closely with international evidence, where 17–25% of shared micromobility trips are typically associated with transit stations^{32,63,81–83}. This convergence suggests that, even at an early deployment stage, DBS already fulfils a non-negligible connection function in Lausanne.

Behavioural differences between ISCA and OSCA trips further support this interpretation. ISCA trips are shorter, temporally concentrated around commuting peaks, and more frequently associated with major rail hubs, consistent with prior work on bike-and-ride and shared micromobility integration^{74,84–87}. The asymmetry between access and egress legs mirrors classical commuting patterns and reinforces the interpretation that DBS primarily provides station-oriented mobility functions^{88,89}.

Although a minority of users accounts for a disproportionate share of ISCA activity, the spatial distribution of trips suggests that potential intermodality is not confined to a niche group but reflects a broader, system-level

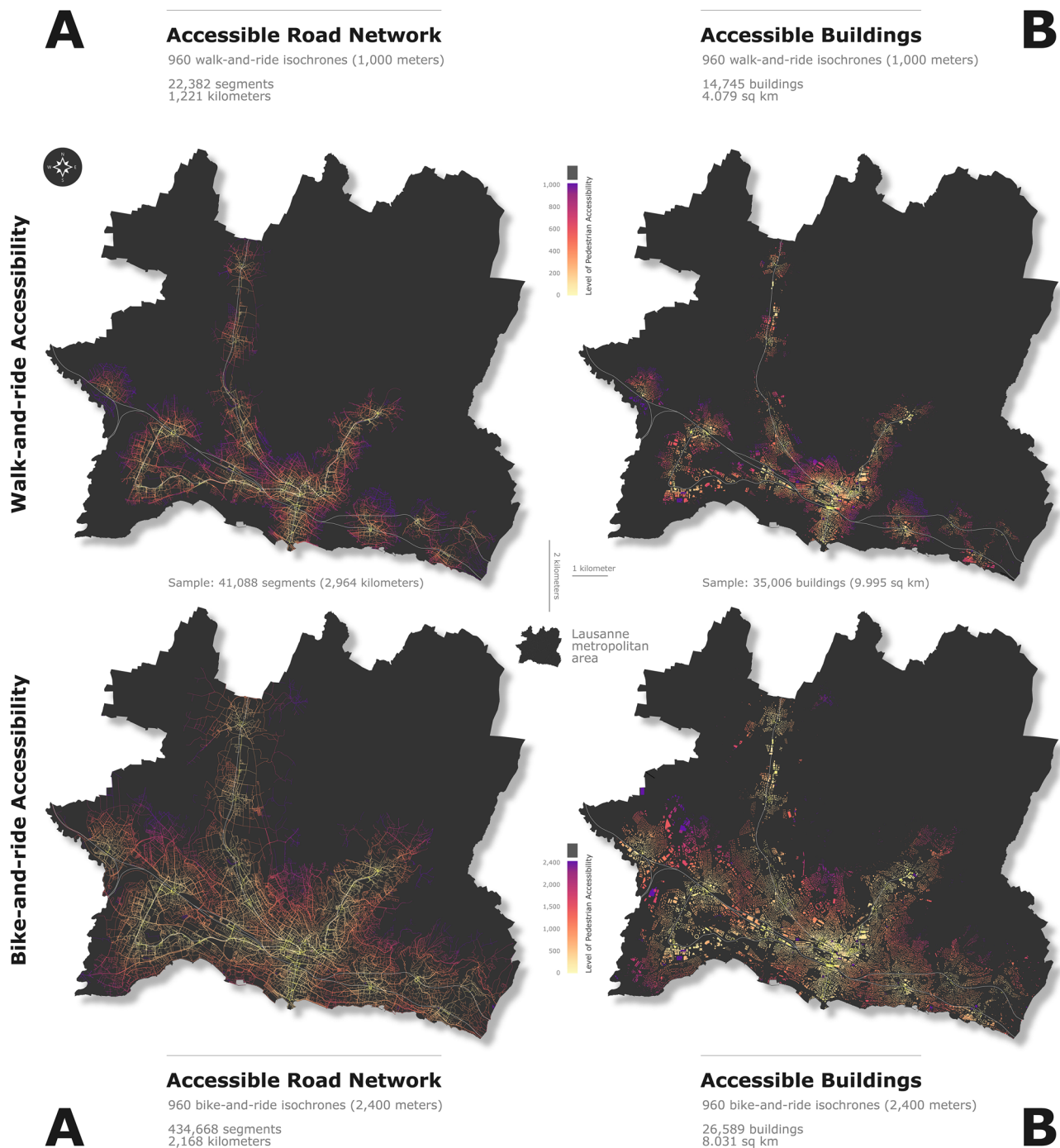


Fig. 13 | Comparative accessibility analysis of walking and cycling catchment areas around railway stations. The figure presents a 2×2 matrix of network-constrained accessibility maps across the Lausanne metropolitan area, comparing walk-and-ride (top row) and bike-and-ride (bottom row) isochrones, and contrasting accessible road network segments (column A) against accessible buildings (column B). All maps are derived from 960 station entry isochrones computed using *OpenTripPlanner* (OTP). **A** Accessible road network under walk-and-ride conditions (1000-m isochrones): 22,382 segments totalling 1221 km are reachable from transit stations on foot, out of a full metropolitan sample of 41,088 segments (2964 km).

Accessible road network under bike-and-ride conditions (2400-m isochrones): 434,668 segments totalling 2168 km are reachable by bicycle from transit stations. **B** Accessible buildings under walk-and-ride conditions (1000-m isochrones): 14,745 buildings covering 4.079 km² are reachable on foot, out of a full sample of 35,006 buildings (9.995 km²). Accessible buildings under bike-and-ride conditions (2400-m isochrones): 26,589 buildings covering 8.031 km² are reachable by bicycle. In all four panels, road segments and buildings are coloured according to the level of pedestrian or cycling accessibility, using a sequential colour scale from light yellow (low accessibility, value: 0) through orange and red to dark purple.

interaction between DBS and the rail network^{90,91}. The observed distances are consistent with widely reported acceptability thresholds for cycling-based transfers and echo the principles underlying compact, transit-oriented, and 15-Minute proximity-centred urban systems^{13,92,93}.

A major contribution of this study lies in quantifying how DBS expands the territorial reach of public transport. By combining empirically

derived spatial and temporal thresholds with network-constrained routing, we show that DBS–rail integration extends station catchment areas well beyond walking isochrones. Accessibility gains are observed across multiple spatial dimensions, including surface coverage, street-network reach, population, employment, and destination access, reflecting Lausanne’s polycentric urban structure^{94–97}.

Table 9 | Significant standardised coefficients ($\hat{\beta}$) from GLM (Y1) and OLS (Y2, Y3) models, ISCA vs OSCA ($p < 0.05$)

X	Y1		Y2		Y3	
	Y _{ISCA}	Y _{OSCA}	Y _{ISCA}	Y _{OSCA}	Y _{ISCA}	Y _{OSCA}
Accessibility (D1)						
Distance to nearest entrance (X1 _A)	−0.020*	−0.114***	–	–	–	–
Distance to Lausanne-Flon and Gare de Lausanne (X1 _B)	–	4.074***	−1.765*	−3.206***	–	−2.424**
Intersections (X2 _B)	0.230***	0.114***	–	–	–	–
Slope (X2 _C)	−0.273***	−0.138***	–	–	–	–
Cycling facilities (X3 _A)	0.147***	0.154***	–	–	–	–
BRT and bus stops (X4 _A)	−0.140***	0.120***	–	–	–	–
PBS stations (X4 _B)	0.305***	0.009*	–	–	–	–
Land use (D2)						
Population density (X5)	0.092***	−0.033***	–	–	–	–
Sector 1 employment (X6 _A)	−0.087***	−0.038***	–	–	–	–
Sector 2 employment (X6 _B)	−0.086***	−0.087***	–	–	–	–
Sector 3 employment (X6 _C)	–	0.027***	–	–	–	–
'Local' POIs (X7 _A)	−0.056***	0.043***	0.108*	0.080*	0.091*	–
'Intermediate' POIs (X7 _B)	−0.156***	−0.035***	–	–	–	–
'Regional' POIs (X7 _C)	0.112***	0.090***	–	–	–	–
Residential (X8 _A)	−0.322***	−0.130***	–	–	–	–
Public services (X8 _B)	−0.087***	−0.156***	–	−0.068*	–	–
Commercial and office (X8 _C)	−0.021**	–	–	0.073*	–	0.071*
Industrial (X8 _D)	−0.030***	−0.194***	–	–	–	–
Farmland (X8 _E)	−0.169***	0.029***	–	–	–	–
Green space (X8 _F)	−0.191***	0.038***	–	–	–	–
Mobility tool and social factors (D3)						
Driving licence (X9 _A)	0.224***	−0.093***	–	–	–	–
Motorisation (X9 _B)	–	0.111***	0.119*	–	–	–
Bicycles (X9 _C)	0.150***	0.029***	0.092*	–	–	–
e-Bikes (X9 _D)	−0.025*	−0.131***	–	0.215***	–	0.197***
Transit pass (X10 _A)	0.133***	–	–	–	–	–
PBS pass (X10 _B)	0.192***	0.029***	−0.108**	–	−0.085*	–
Age (X11 _A)	−0.245***	−0.023***	0.116*	0.084*	0.102*	–
Household size (X11 _B)	–	−0.180***	–	0.126**	–	0.098*
Income (X12)	–	0.181***	−0.197***	−0.080*	−0.215***	–

Only statistically significant coefficients ($p < 0.05$) from pooled global models (all temporal periods combined). Trip count per hexagon (Poisson GLM) for Y1. Median trip distance in metres and trip duration in seconds (OLS) for Y2 and Y3, respectively. All predictors are standardised to z-scores. Missing values (–) indicate non-significant results.

* $p < 0.05$, ** $p < 0.01$, and *** $p < 0.001$.

Beyond residential coverage, these gains also concern access to activity locations that structure daily mobility, such as employment centres and key destinations. This reinforces the idea that the value of intermodal accessibility lies not only in demographic reach but also in the ability to connect households to jobs and services across the metropolitan region.

The regression results highlight a set of structurally consistent determinants that differentiate ISCA from OSCA behaviour, with the clearest contrasts emerging in accessibility and sociodemographic dimensions. Overall, the findings align with existing evidence on bike-and-ride practices, while revealing patterns specific to the DBS–rail interface.

Accessibility-related variables play a central role. Proximity to stations remains a key driver of DBS usage, confirming well-established distance-decay effects. More distinctively, PBS station presence emerges as the strongest positive predictor of ISCA intensity, suggesting a reinforcing effect between shared mobility services and rail nodes. This supports the interpretation of these locations as emerging 'mobility hubs', where shared and public transport modes co-locate and mutually reinforce accessibility⁹⁸.

In contrast, bus stop density exhibits opposite associations for ISCA and OSCA trips, supporting the interpretation of a substitution effect between bus-based feeder trips and cycling in intermodal contexts, particularly during commuting periods. DBS appears to be associated with lower bus-based feeder use, particularly during the morning peak, while reinforcing rail-oriented access. This pattern is consistent with a 'cooperation' dynamic in which cycling may substitute for bus-based feeder trips, primarily during commuting hours⁹⁹.

Network structure also shapes DBS use. Intersection density is positively associated with both intermodal and unimodal activity, reflecting the importance of fine-grained street connectivity for cycling. By contrast, slope retains a negative influence despite electric assistance, indicating that topography continues to act as a structural constraint. In the Swiss context, e-bikes are often considered particularly suited to hilly environments¹⁰⁰, yet our results confirm that while electric assistance mitigates slope-related barriers, it does not eliminate them. In this regard, R  rat¹⁰¹ shows that e-bikes 'flatten' the topography in Switzerland.

Land use patterns further differentiate DBS behaviours. Residential and periurban areas are negatively associated with ISCA activity, while supporting more autonomous cycling, suggesting that intermodal use remains concentrated in denser and transit-oriented environments. Employment-related effects are more nuanced and appear to depend on local spatial structure, with compact urban centres generating shorter and non-intermodal trips.

Sociodemographic factors provide the most distinctive contrasts. Transit pass ownership is strongly associated with ISCA activity, confirming that intermodal cycling is closely tied to public transport use. Younger populations are more likely to engage in DBS–rail combinations, while areas with higher car ownership also show higher ISCA intensity, pointing toward multimodal rather than substitutive behaviour.

Finally, income emerges as a key determinant of trip distance and duration. Higher-income areas are associated with shorter intermodal trips, likely reflecting better proximity to high-quality transit infrastructure. This suggests that the accessibility benefits of DBS are unevenly distributed, with more efficient intermodal patterns concentrated in already well-served areas, echoing broader concerns regarding equity in shared micromobility systems^{102,103}.

Taken together, these results indicate that DBS–rail integration is not solely driven by infrastructure availability, but emerges from the interaction between network conditions, land use, and user characteristics.

Although this study is grounded in the Swiss context, the ISCA proxy was deliberately conceived as a transferable analytical framework. Its underlying logic—identifying DBS trips compatible with public transport access using network-based isochrones and spatiotemporal filters—does not depend on institutional specificities. Sensitivity analyses further indicate that the main determinants of DBS–rail integration remain stable across alternative spatial definitions of station catchment areas, supporting the transferability of the approach.

From a sustainable mobility perspective, these findings highlight the capacity of DBS to act as a flexible complement to rail systems by improving access conditions and extending station catchments. In metropolitan contexts where planning frameworks prioritise multimodality and climate mitigation, shared micromobility can contribute to enhancing the competitiveness of public transport, particularly for short- and medium-distance trips.

This study demonstrates that dockless bikesharing (DBS) can meaningfully strengthen first- and last-mile (FLM) connectivity in medium-sized European cities. By applying a spatiotemporal detection pipeline to high-resolution DBS data and by developing the ISCA proxy, we identify trips that are spatially and temporally compatible with public transport access. Overall, the results indicate that shared micromobility can extend the territorial reach of rail-based transport, improving feeder connections and supporting more integrated and sustainable mobility systems.

Beyond these empirical insights, the study contributes a transferable analytical framework for detecting and analysing bike-and-ride integration patterns. The approach combines multimodal routing with finely resolved walking isochrones, spatial clustering to mitigate GPS imprecision, and origin–destination and temporal filters to distinguish compatible transfers from misclassified or substitutive trips. A diagnostic comparison of global and spatially varying specifications further indicates that global GLM and OLS models provide a robust and parsimonious representation of the data. While some spatial heterogeneity is observed, it remains limited in magnitude and does not substantially alter the interpretation of the main relationships, which appear broadly consistent across the study area.

Several limitations must nonetheless be acknowledged. First, ISCA captures *potential*, rather than confirmed, intermodal behaviour and should be interpreted as an upper bound. Future work should combine operator data with surveys, smartphone traces, or multimodal ticketing data to validate transfer sequences and better capture behavioural diversity. Second, the analysis focuses on rail-based public

transport; extending the framework to dense bus or BRT systems will require refined methods to distinguish genuine transfers from spatiotemporal proximity. Third, the study examines a recently deployed DBS service whose usage patterns are still evolving, calling for longitudinal analyses to assess how integration develops as systems mature. Finally, the associations between the built environment and DBS usage should be interpreted with caution, as transit infrastructure and PBS deployments may be partially endogenous to underlying demand and urban structure. In particular, their spatial concentration in dense urban cores may bias the observed relationships and limit causal interpretation.

An important question concerns the extent to which DBS trips substitute for short walk-and-ride or feeder bus trips, as opposed to expanding the effective catchment area of public transport. Some ISCA-classified trips may indeed replace existing access modes in station-adjacent areas, while others likely enable new connections in locations where public transport would otherwise remain less competitive. Disentangling substitution from expansion effects remains a key avenue for future research.

More broadly, these findings highlight the capacity of shared micromobility to act as a flexible complement to rail systems in supporting multimodal and low-carbon mobility transitions. By extending station accessibility and facilitating FLM connections, DBS can contribute to enhancing the competitiveness of public transport, particularly in urban contexts where improving access conditions remains a central challenge for achieving modal shift.

Data availability

The dockless bikesharing trip data used in this study were provided by Bird under a data sharing agreement and are confidential. They cannot be made publicly available due to commercial restrictions. All other data supporting the findings of this study are available from the corresponding author upon reasonable request.

Received: 2 December 2025; Accepted: 9 April 2026;

Published online: 04 May 2026

References

1. Levine, J., Grengs, J. & Merlin, L. A. *From Mobility to Accessibility: Transforming Urban Transportation and Land-Use Planning* 240 (Cornell University Press, 2019).
2. Molino, M., Rampon, A.-S. & Cipolla, R. Les pratiques d'intermodalité vélo-transport collectifs. 91. <https://www.gart.org/publication/pratiques-dintermodalite-velo-transport-collectifs/> (2015).
3. Brons, M., Givoni, M. & Rietveld, P. Access to railway stations and its potential in increasing rail use. *Transp. Res. Part A Policy Pract.* **43**, 136–149 (2009).
4. Verbavatz, V. & Barthelemy, M. Critical factors for mitigating car traffic in cities. *PLoS ONE* **14**, e0219559 (2019).
5. Guerra, E., Cervero, R. & Tischler, D. Half-mile circle. Does it best represent transit station catchments? *Transp. Res. Rec. J. Transp. Res. Board* **2276**, 101–109 (2012).
6. Bentayou, G. Le Transit-Oriented Development nord-américain : principes et vue d'ensemble. *Articuler urbanisme et transport. Les contrats d'axes français à la lumière du Transit-Oriented development (TOD)*, 56–90. <https://shs.hal.science/halshs-02891975v1> (2015).
7. Sebban, A.-C. *La complémentarité entre vélo et transport public* Thèse de doctorat. Aix-Marseille 3. <http://www.theses.fr/2003AIX32060> (2003).
8. BiTiBi. *Bike. Train. Bike. The Final Report* 49. <http://www.bitibi.eu/> (2017).
9. Oort, N. V. Overview of the research into the combined bicycle and transit mode. TU Delft. <https://nielsvanoort.weblog.tudelft.nl/tag/cycling/> (2020).

10. Lee, J., Choi, K. & Leem, Y. Bicycle-based transit-oriented development as an alternative to overcome the criticisms of the conventional transit-oriented development. *Int. J. Sustain. Transp.* **10**, 975–984 (2016).
11. Ibraeva, A., Almeida Correia, G. H. D., Silva, C. & Antunes, A. P. Transit-oriented development: A review of research achievements and challenges. *Transp. Res. Part A Policy Pract.* **132**, 110–130 (2020).
12. Moinse, D. & L'Hostis, A. Optimizing intermodal commuting by way of detours and breaks: evidence of micromobility users in France. *J. Transp. Geogr.* **116**, 1–16 (2024).
13. Wolanski, M. The potential role of railway stations and public transport nodes in the development of 15-minute cities. *Infrastructures* **8**, 141 (2023).
14. Oostendorp, R. & Gebhardt, L. Combining means of transport as a users' strategy to optimize traveling in an urban context: empirical results on intermodal travel behavior from a survey in Berlin. *J. Transp. Geogr.* **71**, 72–83 (2018).
15. Rabaud, M. & Richer, C. "(Micro)mobilités émergentes et intermodalités. L'irruption des << Engins de Déplacements Personnalisés >> dans les chaînes de mobilité". In: Colloque de la commission de géographie des transports du CNFG : "Les mobilités émergentes. Fondements et conséquences des nouvelles pratiques de déplacement des personnes et d'acheminement des marchandises." <https://halshs.archives-ouvertes.fr/halshs-02318268> (2019).
16. Bortoli, A. D. & Christoforou, Z. Consequential LCA for territorial and multimodal transportation policies: Method and application to the free-floating e-scooter disruption in Paris. *J. Clean. Prod.* **273**, 122898 (2020).
17. Kang, W. "University Students' Adoption and Post-adoption Behaviors of New Mobility Services in China: Three Empirical Essays". PhD thesis, Université Paris-Est. <https://theses.hal.science/tel-03331932> (2020).
18. Richer, C. [dossier mobilités] #11 - micromobilités et intermodalités: l'enjeu des engins de déplacement personnels. <https://www.construction21.org/france/articles/h/dossier-mobilites-9-micromobilites-et-intermodalites-l-enjeu-des-engins-de-deplacement-personnels.html> (2021).
19. Goletz, M., Hausteine, S., Wolking, C. & L'Hostis, A. Intermodality in European metropolises: the current state of the art, and the results of an expert survey covering Berlin, Copenhagen, Hamburg and Paris. *Transp. Policy* **94**, 109–122 (2020).
20. Office fédéral de la statistique & Office fédéral du développement territorial. Microrecensement mobilité et transports. Analyses supplémentaires possibles, 88. <https://www.are.admin.ch/are/fr/home/mobilite/bases-et-donnees/mrmt.html> (2023).
21. Moinse, D. A systematic literature review on station area integrating micromobility in Europe: a 21st century transit-oriented development. in *Smart Cities. Social and Environmental Challenges and Opportunities for Local Authorities* 1st edn. 171–204. <https://link.springer.com/26.1564book/10.1007/978-3-031-35664-3#toc> (Springer, 2023).
22. Rieder, T. *Evaluation of the Social Sustainability of E-scooters: Policy Strategies of Shared Micromobility Regulation in Different Cities of the Canton of Zurich (Switzerland)*. Master's Thesis, ETH Zurich, 86. <https://doi.org/10.3929/ethzb-000723302> (2025).
23. Oeschger, G., Carroll, P. & Caulfield, B. Micromobility and public transport integration: the current state of knowledge. *Transp. Res. Part D Transp. Environ.* **89**, 21 (2020).
24. Zhou, X. et al. The spatially varying effects of built environment characteristics on the integrated usage of dockless bike-sharing and public transport. *Sustain. Cities Soc.* **89**, 104348 (2023).
25. Li, Z., Shang, Y., Zhao, G. & Yang, M. Exploring the multiscale relationship between the built environment and the metro-oriented dockless bike-sharing usage. *Int. J. Environ. Res. Public Health* **19**, 2323 (2022).
26. Brunsdon, C., Fotheringham, A. S. & Charlton, M. E. Geographically weighted regression: a method for exploring spatial nonstationarity. *Geogr. Anal.* **28**, 281–298 (1996).
27. Cardozo, O. D., García-Palomares, J. C. & Gutiérrez, J. Application of geographically weighted regression to the direct forecasting of transit ridership at station-level. *Appl. Geogr.* **34**, 548–558 (2012).
28. Ma, J. et al. The analysis of spatio-temporal characteristics and determinants of dockless bike-sharing and metro integration. *Transp. Lett.* **16**, 182–195 (2024).
29. Ji, Y., Ma, X., Yang, M., Jin, Y. & Gao, L. Exploring spatially varying influences on metro-bikeshare transfer: a geographically weighted poisson regression approach. *Sustainability* **10**, 1526 (2018).
30. Li, W., Chen, S., Dong, J. & Wu, J. Exploring the spatial variations of transfer distances between dockless bike-sharing systems and metros. *J. Transp. Geogr.* **92**, 103032 (2021).
31. Bao, J., Shi, X. & Zhang, H. Spatial analysis of bikeshare ridership with smart card and POI data using geographically weighted regression method. *IEEE Access* **6**, 76049–76059 (2018).
32. Zhang, H. et al. Exploring travel mobility in integrated usage of dockless bike-sharing and the metro based on multisource data. *ISPRS Int. J. Geo-Inf.* **13**, 108 (2024).
33. État de Vaud. Plan directeur cantonal (PDCn). 4e adaptation quarter. Département des institutions, du territoire et du sport, Direction générale du territoire et du logement, 441. <https://vd.pdcn.ch/fr/> (2022).
34. Office fédéral de la statistique & Office fédéral du développement territorial. Comportement de la population en matière de mobilité. Résultats du microrecensement mobilité et transports 2021, 88. <https://www.are.admin.ch/are/fr/home/mobilite/bases-et-donnees/mrmt.html> (2023).
35. 6t-bureau de recherche. La répartition modale du transport de voyageurs en Suisse. Synthèse et enjeux pour les transports publics Berne: LITRA, UTP, ARE, 58. <https://www.are.admin.ch/are/fr/home/media-et-publications/publications/transports/modalsplit-personenverkehr-schweiz.html> (2019).
36. Quantis. Bilan des émissions de gaz à effet de serre du canton de vaud. Année de référence 2019. version 2 État de Vaud, 73. <https://www.vd.ch/environnement/durabilite-et-climat/politique-climatique/les-trois-axes/axe-documentation> (2022).
37. Agglomération Lausanne-Morges. PALM projet d'agglomération lausanne-morges de 5e génération. rapport principal Volume A. État de Vaud, 303. <https://lausanne-morges.ch/rapports/rapport-2025/> (2025).
38. Ville de Lausanne. Observatoire de la mobilité lausannoise. Indicateurs de suivi de la mobilité 2024 10. Lausanne: Ville de Lausanne, Service de la mobilité et de l'aménagement des espaces publics (MAP), 45. <https://www.lausanne.ch/officiel/administration/finances-et-mobilite/mobilite-et-amenagements-publics/publications/observatoire-mobilite.html> (2025).
39. 6t-Bureau de recherche. Analyse du microrecensement mobilité et transports 2015 et comparaison avec les années 2000, 2005 et 2010. Phase 1. rapport final Rapport de recherche 7. Genève: État de Genève, Direction générale des transports, Office cantonal de la statistique ; État de Vaud, Direction Générale de la Mobilité et des Routes, Service Cantonal de recherche et d'information statistique, 184. <https://www.vd.ch/mobilite/oam/enquetes> (2018).
40. Numerus. Pendularité vaudoise : recours au transport public en hausse. 1. État de Vaud, 4. <https://www.vd.ch/etat-droit-finances/statistique/publications/numerus> (2025).

41. DETEC, ARE, OFROU, OFT, OFAC, and OFEV. Mobilité et territoire 2050. Plan sectoriel des transports. Plans sectoriels et conceptions de la Confédération (Art. 13 LAT). Partie Programme. Berne: Confédération suisse, 240. <https://www.are.admin.ch/are/fr/home/developpement-et-amenagement-du-territoire/strategie-et-planification/conceptions-et-plans-sectoriels/plans-sectoriels-de-la-confederation/plan-sectoriel-des-transports-pst/plan-sectoriel-des-transports-pst--partie-programme.html> (2021).
42. État de Vaud. Stratégie cantonale de promotion du vélo à l'horizon 2020 Lausanne: État de Vaud, Département des infrastructures Service de la mobilité, p. 55. <https://www.vd.ch/mobilite/loffre-de-mobilite-a-votre-disposition/informations-aux-communes-mobilite/informations-aux-communes> (2010).
43. État de Vaud. Stratégie cantonale ferroviaire. vision 2050 Lausanne: État de Vaud, Département de la culture, des infrastructures et des ressources humaines (DCIRH) du Canton de Vaud, Direction générale de la mobilité et des routes (DGMR), 81. <https://www.vd.ch/mobilite/loffre-de-mobilite-a-votre-disposition/voies-ferrees/strategie-cantonale-ferroviaire> (2024).
44. Swiss Confederation. Switzerland's second nationally determined contribution under the Paris Agreement 2031–2035. 23. https://www.bafu.admin.ch/bafu/fr/home/themes/climat/info-specialistes/climat--affaires-internationales/_accord-de-paris-sur-le-climat.html (2025).
45. Loi fédérale du 18 mars 2022 sur les voies cyclables. In collab. with Confédération Suisse. <https://www.fedlex.admin.ch/eli/cc/2022/790/fr> (2022).
46. EBP and INFRAS. Perspectives mobilité 2050 pour le canton de Vaud. Rapport technique. Zurich: État de Vaud, Département des infrastructures et des ressources humaines, Direction générale de la mobilité, 113. https://www.vd.ch/fileadmin/user_upload/organisation/dinf/sm/fichiers_pdf/Perspectives_Mobilite%202050_VD.pdf (2022).
47. Ville de Lausanne. Plan climat : base de la politique climatique de la Ville de Lausanne. Rapport-préavis 2020 / 54. Ville de Lausanne, Culture et développement urbain, Sécurité et économie, Sports et cohésion sociale, Logement, environnement et architecture, Enfance, jeunesse et quartiers, Finances et mobilité, Services Industriels, 62. <https://www.lausanne.ch/portrait/climat/publications/rp-plan-climat.html> (2021).
48. OFROU and Conférence Vélo Suisse. Guide pratique. Planification des réseaux de voies cyclables. Documentation sur la mobilité douce 165. 35. <https://www.astra.admin.ch/astra/fr/home/themes/mobilite-douce/publikationenlangsamverkehr.html> (2024).
49. État de Vaud. Plan climat vaudois 2ème génération. Politique climatique du Conseil d'Etat. État de Vaud, 122. <https://www.vd.ch/actualites/communiqués-de-presse-de-letat-de-vaud/detail/communiqué/le-conseil-detat-franchit-une-nouvelle-etape-en-matiere-de-politique-climatique> (2025).
50. SBB CFF FFS. PRODES EA 2035. <https://company.sbb.ch/fr/entreprise/projets/programmes-nationaux/prodes-ea-2035.html>.
51. SBB CFF FFS. Stratégie CFF 2030. 18. <https://company.sbb.ch/fr/entreprise/profil/strategie.html> (2024).
52. État de Vaud. Stratégie cantonale des interfaces de transport de voyageurs. Exposé des motifs et projet de décret 23_LEG_109. 34. https://www.vd.ch/fileadmin/user_upload/organisation/gc/fichiers_pdf/2022-2027/23_LEG_109_TexteCE.pdf (2025).
53. Ville de Lausanne. Nouveau service de vélos électriques en libre-service.lausanne.ch. Section: Nouveau service de vélos électriques en libre-service. https://www.lausanne.ch/apps/actualites/index.php?actu_id=76200 (2024).
54. Antonoff, L. & Martin, P. Bird vient rouler sur les platebandes de PubliBike à lausanne. 24 heures. <https://www.24heures.ch/lausanne-birdvient-rouler-sur-les-platebandes-de-publibike-783752584995> (2024).
55. Lausanne Tourisme. Applications mobiles. <https://www.lausanne-tourisme.ch/fr/applications-mobiles/>.
56. UNIL. Les offres de mobilité active se multiplient à l'UNIL : Bird arrive sur le campus ! <https://www.unil.ch/news/fr/1728996666707> (2024).
57. SharedMobility Booster and Mobilitätsakademie. Projet pilote de système hybride de vélo en libre service par la Ville de Lausanne. <https://www.sharedmobilitybooster.ch/fr/bestpractices/Projet-pilote-de-syst-me-hybride-de-v-lo-en-libre-service-par-la-Ville-de-Lausanne/index.php>.
58. Ville de Lausanne. Location – prêt de vélos. <https://www.lausanne.ch/vie-pratique/mobilite/mobilite-et-circulation/a-velo/informations-pratiques/location-velo>.
59. CHACOMO. Lausanne testet mit dem Anbieter Bird ein hybrides Bikeshaaring-System. <https://www.chacomo.ch/de/News/Lausanne-testet-mit-dem-Anbieter-Bird-ein-hybrides-Bikeshaaring-System-.php> (2024).
60. Forum bikesharing Schweiz. Bird. bikesharing.ch. <https://www.bikesharing.ch/fr/bikesharing/carte-bikesharing-interactive/bird>.
61. Lin, D., Zhang, Y., Zhu, R. & Meng, L. The analysis of catchment areas of metro stations using trajectory data generated by dockless shared bikes. *Sustain. Cities Soc.* **49**, 101598 (2019).
62. Li, X., Yan, Q., Tang, Y. & Luo, C. Identification dockless bike-sharing and metro transfer travelers through mobility chain. *J. Adv. Transp.* **2024**, 4540251 (2024).
63. Ju, M., Martin, E. & Shaheen, S. What is the connection? Understanding shared micromobility links to rail public transit systems in major California cities. *Sustainability* **16**, 555 (2024).
64. Du, J., Meng, C. & Liu, X. Analysis of urban residents' travelling characteristics and hotspots based on taxi trajectory data. *Appl. Sci.* **14**, 1279 (2024).
65. Liu, Y., Li, L., Liu, K., He, M. & Shi, Z. Investigating user preferences for dockless bike- and electric bike-sharing through tracking usage patterns. *Transp. Policy* **169**, 41–55 (2025).
66. Thao, V. T. & Ohnmacht, T. The impact of the built environment on travel behavior: the Swiss experience based on two national travel surveys. *Res. Transp. Bus. Manag.* **36**, 100386 (2020).
67. Beza, A. D., Demissie, M. G. & Kattan, L. A spatiotemporal analysis of shared micromobility trips in first- and last-mile public transit integration. *Transp. Res. Rec.* <https://doi.org/10.1177/03611981251350652> (2025).
68. Fotheringham, A., Brunsdon, C. & Charlton, M. *Geographically Weighted Regression: The Analysis of Spatially Varying Relationships* Vol. 13, 284 (Wiley, 2002).
69. Fotheringham, A. S., Crespo, R. & Yao, J. Geographical and temporal weighted regression (GTWR). *Geogr. Anal.* **47**, 431–452 (2015).
70. Hassam, S., Alpalhão, N. & Neto, M. D. C. A spatiotemporal comparative analysis of docked and dockless shared micromobility services. *Smart Cities* **7**, 880–912 (2024).
71. Zuo, T., Wei, H. & Rohne, A. Determining transit service coverage by non-motorized accessibility to transit: case study of applying GPS data in Cincinnati metropolitan area. *J. Transp. Geogr.* **67**, 1–11 (2018).
72. Hu, S., Chen, M., Jiang, Y., Sun, W. & Xiong, C. Examining factors associated with bike-and-ride (BnR) activities around metro stations in large-scale dockless bikesharing systems. *J. Transp. Geogr.* **98**, 103271 (2022).
73. Li, W. & Joh, K. Exploring the synergistic economic benefit of enhancing neighbourhood bikeability and public transit accessibility based on real estate sale transactions. *Urban Stud.* **54**, 3480–3499 (2017).

74. Ma, X., Ji, Y., Yang, M., Jin, Y. & Tan, X. Understanding bikeshare mode as a feeder to metro by isolating metro-bikeshare transfers from smart card data. *Transp. Policy* **71**, 57–69 (2018).
75. Rabaud, M. & Richer, C. “Quand les engins de déplacement personnel transforment la mobilité urbaine”. In: Les mobilités décarbonnées : un défi global. Cerema. Les Dossiers, CEREMA. 59–62. <https://hal.science/hal-03666504> (2022).
76. Sheller, M. & Urry, J. The new mobilities paradigm. *Environ. Plan. A Econ. Space* **38**, 207–226 (2006).
77. Sheller, M. & Urry, J. Mobilizing the new mobilities paradigm. *Appl. Mobilities* **1**, 10–25 (2016).
78. Randell, R. No paradigm to mobilize: The new mobilities paradigm is not a paradigm. *Appl. Mobilities* **5**, 206–223 (2020).
79. Amar, G. *Homo mobilis : Une civilisation du mouvement* 2nd edn 224 (FYP EDITIONS, 2016).
80. Ewing, R. & Cervero, R. Travel and the built environment. *J. Am. Plan. Assoc.* **76**, 265–294 (2010).
81. 6t-Bureau de recherche. *Étude sur les impacts des services de vélos en free-floating sur les mobilités actives* 86 (ADEME, 2018).
82. Yin, Z. et al. Shared micromobility as a first- and last-mile transit solution? spatiotemporal insights from a novel dataset. *J. Transp. Geogr.* **114**, 103778 (2024).
83. Xing, X., Wan, L. & Luo, F. Demand prediction for shared bicycles around metro stations incorporating STAGCN. *PLoS ONE* **20**, e0328452 (2025).
84. Böcker, L., Anderson, E., Uteng, T. P. & Throndsen, T. Bike sharing use in conjunction to public transport: Exploring spatiotemporal, age and gender dimensions in Oslo, Norway. *Transp. Res. Part A Policy Pract.* **138**, 389–401 (2020).
85. Fan, Y. & Zheng, S. Dockless bike sharing alleviates road congestion by complementing subway travel: evidence from Beijing. *Cities* **107**, 102895 (2020).
86. Qiu, W. & Chang, H. The interplay between dockless bikeshare and bus for small-size cities in the US: a case study of Ithaca. *J. Transp. Geogr.* **96**, 103175 (2021).
87. Kosmidis, I. & Müller-Eie, D. The synergy of bicycles and public transport: a systematic literature review. *Transp. Rev.* **44**, 34–68 (2024).
88. Rietveld, P. The accessibility of railway stations: the role of the bicycle in the Netherlands. *Transp. Res. Part D: Transp. Environ.* **5**, 71–75 (2000).
89. Moinse, D., Goudeau, M., L’Hostis, A. & Leysens, T. “Intermodal use of (e-)scooters with train in the Provence-Alpes-Côte d’Azur region: towards extended train stations areas?” *Environ. Econ. Policy Stud.* **26**, 165–198 (2022).
90. Givoni, M. & Rietveld, P. The access journey to the railway station and its role in passengers’ satisfaction with rail travel. *Transp. Policy* **14**, 357–365 (2007).
91. Reck, D. J., Haitao, H., Guidon, S. & Axhausen, K. W. Explaining shared micromobility usage, competition and mode choice by modelling empirical data from Zurich, Switzerland. *Transp. Res. Part C Emerg. Technol.* **124**, 13 (2021).
92. Moreno, C. *Droit de cité: De la ville-monde à la ville du quart d’heure* 192 (Éditions de l’Observatoire, 2020).
93. Silva, C. et al. Proximity-centred accessibility—a conceptual debate involving planning practitioners worldwide. *Cities* **167**, 106376 (2025).
94. Kager, R., Bertolini, L. & Brömmelstroet, M. T. Characterisation of and reflections on the synergy of bicycles and public transport. *Transp. Res. Part A Policy Pract.* **85**, 208–219 (2016).
95. Geurs, K. T., La Paix Puello, L. & Weperen, S. V. A multi-modal network approach to model public transport accessibility impacts of bicycle-train integration policies. *Eur. Transp. Res. Rev.* **8**, 25 (2016).
96. Marques, R. & Lovelace, R. The potential of ‘bike & ride’ to prioritize investment in suburban cycling and public transport infrastructure: a case study of Seville. *Int. J. Sustain. Transp.* <https://eprints.whiterose.ac.uk/123467/> (2017).
97. Moinse, D. *Le modèle urbain du transit-oriented development revisité par la mobilité individuelle légère émergente. Une investigation dans la région hauts-de-france* Thèse de doctorat, Université Gustave Eiffel, 750 <https://hal.science/tel-05160113> (2025).
98. Hachette, M., L’Hostis, A. & Gragera, A. Exploring the concept of “mobility hubs” and assessing their impacts in two European cities. *Transp. Res. Procedia* **72**, 3497–3504 (2023).
99. Ye, J., Bai, J. & Hao, W. A systematic review of the coepetition relationship between bike-sharing and public transit. *J. Adv. Transp.* **2024**, 6681895 (2024).
100. Stiebe, M. & von Arx, W. Comparative analysis of user characteristics and use patterns in free-floating and station-based e-bike sharing systems - insights from the Basel metropolitan area. In *Proc. STRC 2024 Conference Paper, Swiss Transport Research Conference* 46. https://www.strc.ch/2024/Stiebe_vonArx.pdf (2024).
101. Rérat, P. The rise of the e-bike: towards an extension of the practice of cycling? *Mobilities* **16**, 423–439 (2021).
102. Kampen, J. V., Pauwels, E., Mei, R. V. D. & Dugundji, E. R. Understanding the relation between travel duration and station choice behavior of cyclists in the metropolitan region of Amsterdam. *J. Ambient Intell. Humaniz. Comput.* **12**, 137–145 (2021).
103. Shelat, S., Huisman, R. & Oort, N. V. Analysing the trip and user characteristics of the combined bicycle and transit mode. *Res. Transp. Econ.* **69**, 68–76 (2018).

Acknowledgements

This work was carried out as part of the Sustainability Transformation Research Initiative (STRIVE) project, and specifically in Switzerland by bike! A lever for the ecological and social transformation of mobility (SUàVE!) research group, funded by the University of Lausanne (UNIL). The authors gratefully acknowledge the collaboration and support of the Bird collaborators, whose contribution made this research possible through access to operational data and valuable discussions on shared micromobility integration. The authors also gratefully acknowledge the valuable feedback received during the presentation of this research at the HEC RCGC Research & Practice Seminar held on October 30, 2025, and at the World Conference on Transport Research (WCTR 2026).

Author contributions

D.M.: conceptualisation, methodology, software, formal analysis, investigation, data curation, writing—original draft, visualisation. V.L.: conceptualisation, methodology, validation, formal analysis, investigation, resources, writing—original draft, writing—review and editing, supervision, project administration, funding acquisition.

Competing interests

The authors declare no competing interests.

Additional information

Supplementary information The online version contains supplementary material available at <https://doi.org/10.1038/s44333-026-00104-5>.

Correspondence and requests for materials should be addressed to Virginie Lurkin.

Reprints and permissions information is available at <http://www.nature.com/reprints>

Publisher’s note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Open Access This article is licensed under a Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International License, which permits any non-commercial use, sharing, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if you modified the licensed material. You do not have permission under this licence to share adapted material derived from this article or parts of it. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by-nc-nd/4.0/>.

© The Author(s) 2026