

Affordable accessibility by design: An equity-focused framework for Cooperative, Connected and Automated Mobility (CCAM) integration into public transport

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ABSTRACT

Cooperative, Connected and Automated Mobility (CCAM) is recognised for its potential to complement public transport (PT), particularly through first-mile (FM) and last-mile (LM) services. However, when assessing accessibility improvements, existing literature predominantly focuses on ex-post evaluations of predefined integration scenarios, offering limited guidance on how to strategically deploy CCAM to maximise societal benefits. To the best of our knowledge, no framework jointly addresses accessibility and affordability constraints in a CCAM context at the strategic planning stage.

This study proposes a strategic planning framework for PT-CCAM integration by defining an affordable accessibility measure that incorporates both travel time and generalised monetary cost within a cumulative opportunity structure. It first evaluates baseline PT performance and incorporates a vulnerability assessment to identify Priority Intervention Areas (PIAs), where high socioeconomic disadvantage coincides with low PT-based accessibility. It subsequently applies a two-phase optimisation to close affordable accessibility gaps while minimising individual travel costs.

The framework was validated in Barcelona using neighbourhood-level socioeconomic indicators and ten categories of points of interest (POIs). Results demonstrate that equity-targeted integration improved access to essential opportunities while maintaining affordability. On average, affordable accessibility increased by 18.1% across all POI groups, with gains concentrated in disadvantaged areas. This led to significant reductions in inequality, as shown by a 38.8% improvement in the Corrected Concentration Index (CCI) and a 57.6% reduction in the second-order Foster-Greer-Thorbecke (FGT₂) index.

Findings show that CCAM integration can support more equitable mobility when strategically guided by accessibility and affordability objectives, providing a practical basis for user-centred decision-making.

1. Introduction

Urban transport systems have undergone a profound transformation over the past decade, driven by rapid technological innovation and the emergence of new service models such as shared mobility and platform-based on-demand services (Shaheen & Cohen, 2018; Shaheen, 2018; Sperling, 2018; Huang et al., 2023). These developments are often promoted as key levers to expand individuals' accessibility to jobs, education, healthcare, and other opportunities, thereby enabling greater participation in daily activities and supporting broader social inclusion (Church et al., 2000; Kenyon et al., 2003; Lucas, 2019).

Among emerging transport solutions, Cooperative, Connected and

Automated Mobility (CCAM) is expected to play an important role. CCAM solutions represent a significant opportunity to enhance the urban transport landscape by providing a more efficient, safer, sustainable, and accessible transport system (Martínez-Díaz et al., 2019; Richter et al., 2021; Harrison et al., 2022). Studies suggest that automation and connectivity can increase effective road capacity and stabilise traffic flow, particularly under motorway and urban expressway conditions (Aittoniemi, 2022; Liu et al., 2023). They may also enhance road safety by reducing traffic conflicts and crash risk, especially as the penetration of connected and automated functions increases (Papadoulis et al., 2019; Yang & Fisher, 2021; Matin & Dia, 2023). During the transitional phase, however, these safety gains are heavily

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contingent upon the interactions between automated systems and conventional vehicles, as well as specific deployment strategies such as dedicated lanes (Martínez-Díaz et al., 2019). In addition, smoother driving, platooning, and more efficient speed management can reduce energy use and emissions, although these benefits may be partly offset by rebound effects such as induced travel demand (Taiebat et al., 2018; Silva et al., 2022; Liu et al., 2023; Martínez-Díaz et al., 2024).

However, the true societal value of automation is not guaranteed by technological capability alone. It depends fundamentally on how these systems are deployed, priced, and integrated into existing transport systems (Alonso Raposo et al., 2018; Etmiani-Ghasrodashti et al., 2021; Othman, 2022). Extensive research on transport-related social exclusion and mobility justice shows that many emerging mobility services, including shared systems (such as ride-hailing and bike or scooter sharing) and app-based solutions, primarily serve specific areas and/or sociodemographic groups, particularly younger, higher-income, and digitally connected users. Consequently, other populations are often underserved or further marginalised, reinforcing existing inequalities in access and social participation (Riggs, 2018; Sheller, 2018; Lucas, 2019).

Existing research has characterised the operational impacts of automated mobility, using simulation to examine fleet sizing and network efficiency (Liang et al., 2016; Wen et al., 2018; Salazar et al., 2018; Shen et al., 2018; Levin et al., 2019). While accessibility analyses have also been undertaken, they have typically relied on time-based measures (Meyer et al., 2017; Cohn et al., 2019), activity-based accessibility (ABA) measures (Nahmias-Biran et al., 2021a, 2021b), or utility-based measures (Childress et al., 2015). In these contexts, accessibility is frequently treated as an ex-post outcome of tentative predefined scenarios, a 'what-if' result, rather than a proactive guiding objective for the design of the integration itself. Furthermore, while the importance of accessibility and affordability is increasingly recognised, these dimensions, along with related distributive assessments, are rarely incorporated as direct objectives within the formal mathematical frameworks used to optimise CCAM integration in the existing transport networks. This gap is particularly critical in metropolitan and rural contexts where, despite high levels of public transport (PT) coverage, spatial and socioeconomic inequalities persist (Imhof et al., 2020; Prioleau et al., 2020). Consequently, evaluating the success of PT-CCAM integration requires a robust framework that simultaneously reconciles temporal efficiency, monetary cost, and distributive justice.

Accordingly, this study is guided by three research questions (RQs). RQ1: Can the integration of CCAM with PT alleviate accessibility inequalities? RQ2: How can travel time and generalised cost be jointly considered during the strategic planning of equitable PT-CCAM integration? RQ3: How should zones for early deployment be prioritised during a phased rollout?

In this context, this study addresses the strategic integration of PT and CCAM around the concept of affordable accessibility using a cumulative opportunity (CO) accessibility measure. This choice reflects the practical strengths of CO measures, which are straightforward to implement, interpret, and communicate (Geurs & Van Wee, 2004; El-Geneidy & Levinson, 2006; Boisjoly & El-Geneidy, 2016; Pereira et al., 2024). However, most CO-based applications define accessibility using a threshold on a single impedance dimension, most commonly travel time (Pereira, 2019). Other accessibility analyses rely on generalised travel cost formulations that combine time and monetary components into a single scalar metric (El-Geneidy et al., 2016; Abdelwahab et al., 2021; Cats et al., 2022). In such approaches, time and cost are typically aggregated through Value of Time (VoT) or wage-based conversions, enabling substitution between dimensions within a single unified metric. While analytically convenient, this structure allows full compensation between time and money and may blur the distinct constraints each dimension imposes on users.

In contrast, this research develops a two-dimensional time-cost CO framework inspired by a dual-constraint accessibility logic proposed by

Pereira et al. (2024). Accessibility is recognised only when both travel time and total perceived monetary burden independently satisfy predefined thresholds. The monetary dimension is comprehensively captured through a Total Generalised Travel Cost (TGTC) formulation that incorporates fares, riding costs, monetised travel time, and time-related disutilities such as those associated with waiting, walking, and transfers. Travel time, however, remains a separate constraint rather than being absorbed into a single compensatory metric. By preserving this dual structure, the framework avoids full substitution between dimensions and ensures that accessibility is achieved only when journeys are both temporally reasonable and economically acceptable.

To operationalise this concept, the study uses a methodology that begins with a baseline assessment of affordable accessibility to identify priority intervention areas (PIAs) where high socioeconomic vulnerability intersects with low PT service levels. It then applies a multi-objective optimisation to configure complementary CCAM services designed to close affordable accessibility gaps while strictly constraining the maximum TGTC for individual users. The process concludes with a comparative equity evaluation using formal inequality metrics to quantify the intervention's success in reducing transport poverty. In particular, the Palma ratio, the Corrected Concentration Index (CCI) and the second-order Foster-Greer-Thorbecke (FGT₂) index are used.

By embedding affordable accessibility directly into the optimisation logic, this framework shifts the analytical focus from aggregate system performance to user-centred, equity-oriented strategic planning. It is validated through its application to the city of Barcelona, which has a mature PT system but still exhibits disparities across areas.

The remainder of the paper is organised as follows: Section 2 reviews the existing literature on CCAM and its integration with PT. Section 3 presents the proposed methodological framework, which is subsequently applied to the Barcelona case study in Section 4. Section 5 reports the results of the affordable accessibility and equity assessments. Section 6 discusses the findings and their policy implications, while Section 7 summarises the study's main contributions, acknowledges its limitations, and outlines directions for future research.

2. Literature review

This section summarises previous research on the equitable introduction of CCAM as a means to reduce transport and accessibility disparities. As CCAM-focused works are still scarce, related works targeting other forms of automation such as shared autonomous vehicles (SAVs) or robotaxis are also considered. Note that the latter could be CCAM, but most works do not clarify this aspect.

2.1. Introduction of shared automated solutions into mobility systems

Several studies have highlighted the transformative potential of SAV systems, particularly their capacity to reduce private vehicle ownership and reshape travel behaviour (Fagnant & Kockelman, 2014; Zhang et al., 2018; Menon et al., 2019). Moreover, SAVs can enhance PT efficiency for travellers by improving network connectivity, thus reducing private car dependency, especially when integrated into existing transit networks to complement conventional services (Smolnicki & Soltys, 2016; Krueger et al., 2016; Milakis et al., 2017a; Malokin et al., 2019; Faisal et al., 2019).

Despite this potential, these benefits are highly dependent on deployment strategies and the regulatory context (Milakis et al., 2017b). Without coordinated planning, SAVs may increase vehicle kilometres travelled (VKT) due to empty repositioning trips (De Souza et al., 2020; Morfeldt & Johansson, 2022), induce modal shifts away from PT or attract individuals who would otherwise utilise active transport (i.e., walking and cycling) (Bösch et al., 2018; Cyganski et al., 2018; Pakusch et al., 2018; Soteropoulos et al., 2019), thereby exacerbating congestion and emissions (Salazar et al., 2018). These risks are particularly relevant in cities with mature, high-capacity PT networks, where poorly

integrated automated services may undermine existing public systems (Cohen & Cavoli, 2019). In response, SAVs are increasingly framed as complementary services rather than substitutes for PT, a framing that is also positively perceived by potential users (Nordhoff et al., 2019). Consistent with this, evidence indicates that PT users are the most receptive to SAV services (Heubeck et al., 2023).

2.2. Methodological approaches to PT-AV integration

The scientific literature exploring the integration of PT and AVs in their different forms relies on a diverse set of analytical techniques. Carrese et al. (2023) identify three primary methodological traditions in SAV (or shared CCAM services) integration research: simulation-based models, optimisation frameworks, and behavioural modelling approaches. Within the first tradition, simulation models, including agent-based and microscopic traffic simulation platforms, are widely used to examine fleet performance, waiting times, occupancy rates, and network impacts. For example, Shen et al. (2018) used an agent-based simulation to evaluate a first-mile (FM) PT-SAV integration strategy across multiple fleet size scenarios, finding potential improvements in service efficiency and performance. Their results demonstrated that by replacing 40% of low-demand routes with a minimal SAV fleet, the system could maintain existing service quality while still covering 90% of total passenger demand. Similarly, Wen et al. (2018) simulated a transit-oriented PT-AV system in which SAVs supported both FM rail access and local trips, with demand and supply modelled iteratively. Their results demonstrated that implementing ride-sharing can reduce fleet size by 60% while maintaining a 99% service rate, provided that vehicles can accommodate at least four passengers. Expanding this to a regional scale, Huang et al. (2021) evaluated SAV fleets around Austin, Texas. The study utilised a 10% sample of regional travel demand to perform a micro-simulation using the open-source SUMO (Simulation of Urban MObility) tool (Krajewicz, 2010). Results indicated that with SAVs serving FM or last-mile (LM) requests in designated districts, approximately 3.71% of person-trips shifted from private cars to the SAV-and-ride mode. Collectively, these studies demonstrate that SAV feeders can improve operational performance and reduce solo driving under appropriate conditions.

Parallel to simulation efforts, optimisation-based models concentrate on system-level efficiency. A multi-commodity network flow problem was formulated by Salazar et al. (2018) to coordinate autonomous mobility-on-demand (AMoD) and PT for the joint minimisation of users' travel time and operational costs. In a case study involving approximately 54,000 taxi rides in Manhattan, electric lightweight vehicles were utilised in the system's design. It was demonstrated that travel times and total costs could be reduced by more than 40% through intermodal coordination. In addition to network flow problems, integer and linear programming models have been developed to optimise fleet allocation, routing, and intermodal assignment. For example, two integer programming (IP) models were developed by Liang et al. (2016) to optimise the service area and trip selection for an automated taxi system providing first-mile last-mile (FMLM) connectivity to train stations, showing that fleet size was a critical factor for profitability. Along the same lines, a linear programming (LP) model was developed by Levin et al. (2019) to optimally integrate SAVs as a LM mode with PT, with the objective of minimising total system travel time. In a case study of the Sioux Falls network, it was demonstrated that using SAVs significantly reduced traveller waiting times and overall system travel times, particularly when fleet sizes were small.

In contrast to these system-oriented approaches, behavioural modelling studies examine attitudes towards AV ride-sourcing and AV-transit integration. Wali and Khattak (2022) used a joint behavioural model to study how people perceive two types of SAV services. The results showed that living in a walkable area and already using sustainable transport or digital tools significantly increased interest in adopting SAV services. Further exploring public perception, Song et al.

(2021) examined public attitudes in small urban areas towards three forms of AV-transit integration: standalone SAV systems, AVs as FM and LM services connecting users to and from PT, and automated high-capacity transit such as automated buses. They found that respondents generally welcomed AV-transit integration but remained uncertain about its likely impacts. Technology-savvy respondents showed greater interest in these systems, although they also expressed more concerns, while current transit users tended to hold more positive views than non-users.

While these three traditions provide valuable insights into operational planning and user adoption patterns, they primarily prioritise overall system efficiency at an aggregate level. Consequently, performance is typically measured through indicators such as vehicle-kilometres travelled (VKT), waiting times and fleet occupancy, rather than through location-specific measures of spatial accessibility (Narayanan et al., 2020; Golbabaie et al., 2021). At best, accessibility remains a secondary, ex-post outcome rather than a primary objective in network design. This treatment of accessibility is also common in conventional transport planning (Miller, 2020).

2.3. Accessibility and equity implications of automated mobility

As explained, despite the rapid growth of research on automated mobility services, relatively few studies have examined their accessibility and equity implications. Most contributions have evaluated pre-defined AV integration scenarios and assessed impacts ex-post rather than designing accessibility-targeted interventions.

Time-based accessibility measures have been used to examine how AV deployment may alter access under different ownership and service models. Meyer et al. (2017) analysed the national impacts of Level 3 and 4 AVs (SAE International, 2021) in Switzerland under partially automated, fully autonomous private-ownership and shared-fleet scenarios. Using a gravity-type measure of workplace accessibility based on car travel times, they found that the shared AV scenario could increase population-weighted accessibility by 10.3% under optimistic road-capacity assumptions, although the effects were spatially uneven. Adopting a similar time-based approach, Cohn et al. (2019) examined AV futures in the Washington, D.C. region and found that single-occupancy AVs increased job accessibility by 22%, while high-occupancy services produced a substantially larger improvement of 118%.

In addition to these time-based measures, utility-based measures have also been applied. Childress et al. (2015) assessed AV impacts in the Seattle region using the SoundCast activity-based travel demand model, measuring accessibility through aggregate tour mode-destination logsum indicators. In the most optimistic private AV scenario, in which all privately owned cars were assumed to be automated, accessibility increased for most households, with the largest gains occurring in peripheral and rural areas rather than in the already well-served urban core. From an equity perspective, however, the gains were distributed quite evenly across income groups, with aggregate logsum increases of 8.5% for low-income households and 8.9% for high-income households.

For their part, Nahmias-Biran et al. (2021a) applied an activity-based accessibility (ABA) measure to evaluate the impacts of shared AMoD services in Singapore. The study compared a near-future central business district restriction with long-term city-wide deployment, and the latter performed better, producing a median ABA gain of 0.53 minutes and 1.08 Singapore \$. In a subsequent study, Nahmias-Biran et al. (2021b) conducted a cross-city analysis across three prototype cities using a person-level ABA measure. They compared AMoD operating in direct competition with PT with AMoD limited to FM and LM rail access and local circulation, finding that the former produced greater accessibility gains for underserved population segments.

Moreover, while the studies above assess accessibility as experienced by travellers, Whitmore et al. (2022) examined the cost of improving

equitable transit coverage. Transit coverage was defined by comparing transit supply, based on stops, routes and service frequency, with the needs of transit-dependent populations at the census-block-group level. Priority areas were identified as census block groups with low transit coverage and above-average shares of low-income or minority populations. The study then compared three alternatives for providing the same feeder connection from these areas to the nearest adequately served transit stop: conventional buses, four-passenger SAVs and twelve-passenger electric autonomous shuttles. The automated options were therefore assessed as complements to the existing PT network. Across the three analyses, SAVs recorded the lowest cost per passenger-kilometre travelled (PKT), ranging from \$0.77 to \$0.90 per PKT. The findings therefore indicate that SAVs and autonomous shuttles could improve transit equity at lower average operating costs than conventional buses.

Taken together, existing research shows that automated mobility can generate accessibility benefits, especially when integrated with PT and deployed as shared service modes. However, the literature remains divided across distinct focus areas, including operational optimisation, scenario-based accessibility assessment, and equity- or coverage-oriented evaluation. While these studies offer valuable insights, they rarely integrate all key factors into a single framework. Most studies either overlook the joint consideration of travel time and monetary cost as separate dimensions within CO-based accessibility or combine them into a single generalised cost metric. Although some models assess how outcomes are distributed across vulnerable areas, none explicitly optimise PT-CCAM integration to reduce affordable accessibility gaps. This study addresses this methodological gap by introducing a structured, equity-focused framework whose contributions mirror the successive stages of the proposed methodology.

2.4. Research contributions

To bridge the identified gaps in the current literature, this research offers several distinct contributions to the integration of automated mobility and transport equity.

First, the study introduces a novel, policy-friendly affordable accessibility framework for the equitable integration of CCAM services. Rather than relying on complex and highly data-demanding activity-based indicators, or on purely unidimensional time-based measures, accessibility is defined using a CO-based metric subject to explicit travel time and monetary cost thresholds, making the approach more transparent, data-streamlined, and easier to communicate in policy contexts. The framework integrates travel time and monetary burden within a unified affordability structure in which accessibility is recognised only when both temporal and economic conditions are satisfied. By combining generalised monetary travel cost with separate travel time thresholds, it ensures that improved connectivity does not come at the expense of excessive financial burden.

Second, it links accessibility with socioeconomic vulnerability to guide targeted interventions. Low accessibility alone does not necessarily imply deprivation. The study therefore intersects affordable accessibility with structural socioeconomic indicators to identify PIAs. This vulnerability-informed targeting ensures that PT-CCAM integration is directed towards zones where limited access coincides with genuine transport poverty, strengthening vertical equity considerations.

Third, it operationalises structured PT-CCAM integration through FM, LM, and FMLM configurations. Unlike much of the literature that evaluates AVs as system-wide substitutes or as fixed, *a priori* additions, this study considers all possible combinations to identify the most suitable configuration for each case.

Fourth, the study adopts a user-centred optimisation logic. The integration model constrains the maximum generalised cost experienced by any user rather than minimising aggregate system averages. This reflects the behavioural reality that individuals experience a single chosen path. By prioritising the highest individual burden, the

framework shifts the focus from system efficiency to user-level affordability.

Fifth, it evaluates equity both before and after the intervention. Beyond measuring accessibility gains, the study assesses distributive impacts through pre- and post-integration equity analysis. This enables an explicit examination of whether PT-CCAM integration reduces disparities and alleviates transport poverty.

Taken together, this research repositions PT-CCAM integration from ex-post scenario comparison to targeted, affordability-sensitive, and equity-oriented accessibility improvement. By combining an interpretable CO metric, dual time-cost constraints, vulnerability-informed targeting, structured integration, user-centric optimisation, and pre- and post-intervention equity evaluation, the framework provides a coherent and policy-relevant approach for inclusive urban mobility strategic planning.

3. Methodology

The proposed methodological framework, as shown in Fig. 1, consists of six stages: (1) data preparation, (2) baseline affordable accessibility assessment, (3) vulnerability analysis, (4) PT-CCAM integration and optimisation, (5) equity assessment, and (6) interpretation of findings.

In the first stage, appropriate spatial analysis zones are defined as core units of analysis, and population-density-weighted centroids are used to represent trip origins and destinations. Points of interest (POIs) are categorised into customised activity groups and aggregated at the zone level by summing the number of individual POI records located within each zone boundary, yielding a zone-level opportunity count for each activity group. Multimodal PT network data (before CCAM integration), including routes, stops, and timetables across available PT modes, are assembled for routing. Zone-level socioeconomic indicators are also compiled to support the vulnerability assessment.

Subsequently, baseline PT performance is evaluated through multimodal routing between all origin-destination (OD) pairs, generating detailed travel itineraries. Travel times derived from these itineraries serve as the raw temporal metrics for accessibility. To define opportunity reachability, activity-specific time thresholds are introduced to represent the maximum duration users are willing to spend reaching a destination. To further integrate temporal and monetary dimensions, a TGTC function is adapted from established generalised cost formulations (Abdelwahab et al., 2021; Karakurt & Gokasar, 2024), as defined in Eq. (1). The TGTC combines mode-specific fares and distance-based riding costs with monetised time components, including in-vehicle time (IVT) and weighted penalties for walking, waiting, and transfers. Together, this formulation yields a unified metric of travel effort that captures both financial burden and perceived time disutility, forming the basis of the affordability analysis.

$$TGTC = \left(\sum_{m \in M} F_m + (RC_m \cdot D_m) + (VoT_m \cdot IVT_m) \right) + \left(VoT_{PT} \cdot \left(\alpha \cdot WT + \beta \cdot WkT + \gamma \cdot \sum_{k=1}^{NT} TT_{m_k, n_k} \right) \right) \quad (1)$$

Where TGTC is expressed in euros (€) and $m \in M$ denotes the set of transport modes. For each mode, the cost includes a base fare F_m (€), a distance-based riding cost $(RC_m \cdot D_m)$ calculated as the per-kilometre cost coefficient RC_m (€/km) multiplied by the distance travelled D_m (km), and the monetised value of on-board travel time $(VoT_m \cdot IVT_m)$, computed as the VoT_m (€/h) multiplied by IVT_m (h). In addition to these direct components, the TGTC accounts for indirect travel burdens, including total waiting time WT (h) and walking time WkT (h), and the number of transfers NT . WT and WkT are weighted by coefficients α and β to reflect their higher perceived disutility relative to IVT_m . Transfers are modelled through transfer-type-specific time penalties, expressed in hours per

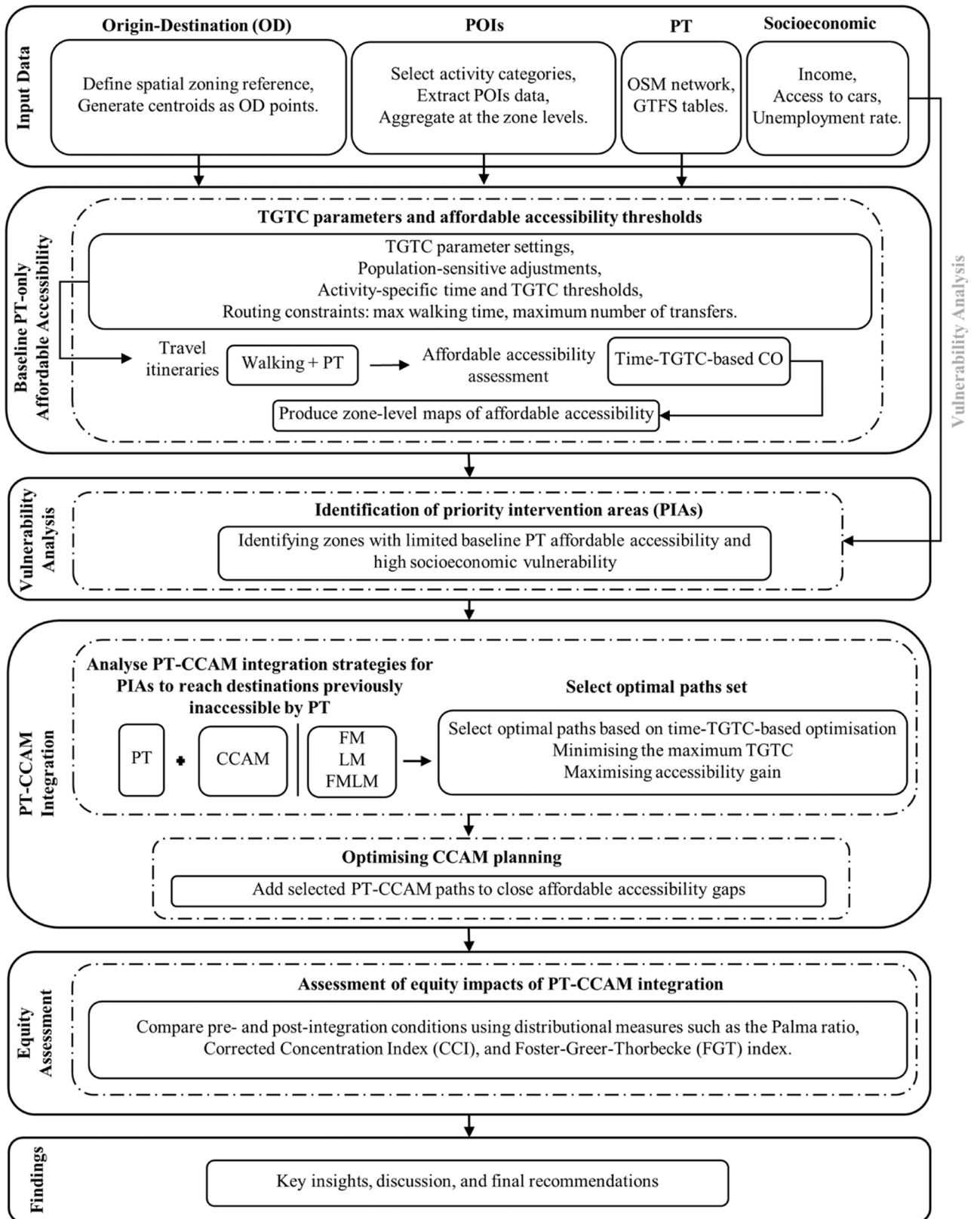


Fig. 1. Overview of the methodological framework.

interchange, TT_{m_k, n_k} , where k indexes each individual transfer. For each transfer k , TT_{m_k, n_k} depends on the specific combination of arrival mode m_k and departure mode n_k , such as bus-bus, bus-metro, or bus-CCAM, reflecting the varying physical and psychological costs associated with

different intermodal transitions. These penalties are monetised using VoT_{PT} , weighted by the coefficient γ , and summed across all NT transfers.

Affordable accessibility is measured using a dual-constraint CO in-

indicator, which counts the number of opportunities reachable from an origin within predefined time and cost thresholds, as defined in Eqs. (2)–(4).

$$A_i = \sum_{j=1}^n O_j f(t_{ij}) h(g_{ij}) \quad (2)$$

$$f(t_{ij}) = 1 \text{ if } t_{ij} \leq T; 0 \text{ otherwise.} \quad (3)$$

$$h(g_{ij}) = 1 \text{ if } g_{ij} \leq G; 0 \text{ otherwise.} \quad (4)$$

Eq. (2) is applied separately for each POI category. In this equation, A_i denotes the affordable accessibility of origin zone i . The index j denotes a destination zone, and n is the total number of destination zones considered in the study area. O_j represents the number of opportunities of the selected POI category located in zone j . The term t_{ij} is the travel time from origin i to destination j , while g_{ij} is the corresponding TGTC between the OD pair. The binary function $f(t_{ij})$ equals 1 when t_{ij} does not exceed the time threshold T , and 0 otherwise. Similarly, $h(g_{ij})$ equals 1 when g_{ij} does not exceed the generalised monetary cost threshold G , and 0 otherwise.

Once underserved zones, defined as those with low baseline PT-only affordable accessibility, are identified, a vulnerability analysis is conducted to determine whether this limited access translates into actual transport poverty. This step functions as a complementary diagnostic layer to the CO framework, recognising that low PT accessibility alone does not necessarily imply disadvantage. For example, in Europe, residential sorting patterns across urban contexts display significant heterogeneity. While central urban gentrification and inner-city renewal attract in some cases highly qualified, high-income households (Hochstenbach & Musterd, 2018; López-Gay et al., 2020), another clear affluent suburbanisation trend coexists: in many continental European regions, a substantial segment of higher-income households chooses to reside in lower-density peripheral areas, prioritising larger living spaces and car-oriented lifestyles over peripheral PT provision (Hesse & Siedentop, 2018). Consequently, while some areas may be identified as zones with low PT-only accessibility, they do not necessarily suffer from true transport poverty.

To distinguish structural disadvantage from spatial accessibility limitations, zones characterised by constrained socioeconomic conditions are defined as socially vulnerable zones. These are identified through zone-level indicators such as income, car access, employment, education, housing burden, and migrant share. A relative quartile threshold is adopted to identify zones experiencing comparatively high disadvantage. The most disadvantaged quartile provides a transparent and reproducible screening criterion while avoiding reliance on an absolute threshold that may not be transferable across contexts. A union-based rule is then applied, whereby disadvantage in at least one of the selected socioeconomic indicators is sufficient for classification. This allows the framework to capture different forms of vulnerability that may contribute to transport poverty. This logic is conceptually consistent with multidimensional deprivation measures such as the EU At Risk of Poverty or Social Exclusion (AROPE) indicator, under which meeting at least one criterion is sufficient for classification (Eurostat, n.d.). Zones that are simultaneously accessibility-underserved and socially vulnerable are defined as PIAs. This classification is applied analytically to every zone: a zone is designated as a PIA only where both conditions, i. e., low PT accessibility and social vulnerability, hold within the same spatial unit.

Building upon the identification of PIAs, the integration stage begins by generating a comprehensive search space of all possible FM, LM, and FMLM connections to complement the existing PT network. From this initial pool, candidate itineraries are pre-filtered based on mandatory travel time and TGTC thresholds to establish a set of feasible PT-CCAM paths. Subsequently, a two-phase optimisation model selects the final set

of paths required to elevate the origin zone's affordable accessibility to at least a predefined target level (i.e., A_T), while balancing individual user costs and operational deployment feasibility.

From a user's perspective, individuals experience only the cost of the single path they use; therefore, the selection process should prioritise minimising the maximum TGTC that any user may face. From the operator's perspective, however, selecting a large number of paths increases deployment complexity, making it desirable to minimise the total number of selected paths. Accordingly, the selection approach should balance user affordability with deployment feasibility to avoid solutions that are either too costly for individuals or too complex to implement. It is important to note that while travel time is not an explicit objective function in this phase, it remains a critical constraint; it serves as a primary component of the TGTC and dictates the accessibility contribution by determining which destinations are reachable within the mandatory temporal thresholds.

To operationalise the trade-off between user affordability and operational complexity, a two-phase lexicographic multi-objective optimisation framework is adopted. In a lexicographic formulation, the objectives are ordered by priority and optimised sequentially, ensuring that a lower-priority objective cannot worsen the optimum already obtained for a higher-priority objective. In Phase 1, the model first aims to eliminate, or otherwise minimise, the accessibility shortfall relative to the target accessibility level A_T and subsequently minimises the maximum TGTC among the selected paths, establishing an initial upper bound for individual travel costs. The resulting initial accessibility gain, maximum TGTC and POI-weighted average TGTC are retained as reference values for Phase 2.

In Phase 2, a user cost tolerance buffer, defined as a percentage increase over the Phase 1 maximum TGTC, permits a limited relaxation of this initial cost ceiling. Within this bounded relaxation, the model considers alternative combinations of feasible paths and maximises the number of newly accessible POIs, representing the accessibility gain. The Phase 2 solution is accepted only if it provides at least the specified additional accessibility gain and results in a POI-weighted average TGTC that is lower than the Phase 1 value by at least a specified minimum; otherwise, the Phase 1 solution is retained. Any tolerated increase in the highest individual cost is therefore conditional on both greater access to opportunities and a lower average cost of reaching those opportunities. The optimisation is conducted independently for each origin zone and POI group, with at most one feasible path selected for each destination zone, avoiding multiple connections to the same destination. The optimisation sequence is summarised in Fig. 2.

As a simple illustration, consider an origin zone with baseline affordable accessibility of 80 POIs and a target level of 100, giving an accessibility gap of 20 POIs. Before optimisation, all candidate PT-CCAM paths are pre-filtered against the travel-time and TGTC thresholds. The paths satisfying both thresholds are defined as feasible paths and are the only paths considered in the next steps.

In Phase 1, Step 1, the model minimises the accessibility shortfall. Suppose that the feasible paths can collectively provide access to more than the 20 additional POIs required, resulting in zero shortfall. In Step 2, the model compares all combinations of feasible paths that achieve this same minimum shortfall and chooses the combination with the lowest maximum TGTC. Here, a solution refers to the set of feasible paths finally selected by the model for the particular origin zone and POI group. Suppose that the Phase 1 solution provides access to 24 additional POIs, with a maximum TGTC of €7.40 and a POI-weighted average TGTC of €7.10.

Phase 2 then examines whether an alternative combination of feasible paths, i.e., another solution, can provide greater accessibility while allowing only a limited increase in the maximum TGTC. For illustration, suppose that the user cost tolerance buffer is set at 10%, meaning that no selected path may exceed €8.14. Suppose also that a Phase 2 solution is accepted only if it makes at least one additional POI reachable and results in a POI-weighted average TGTC that is at least

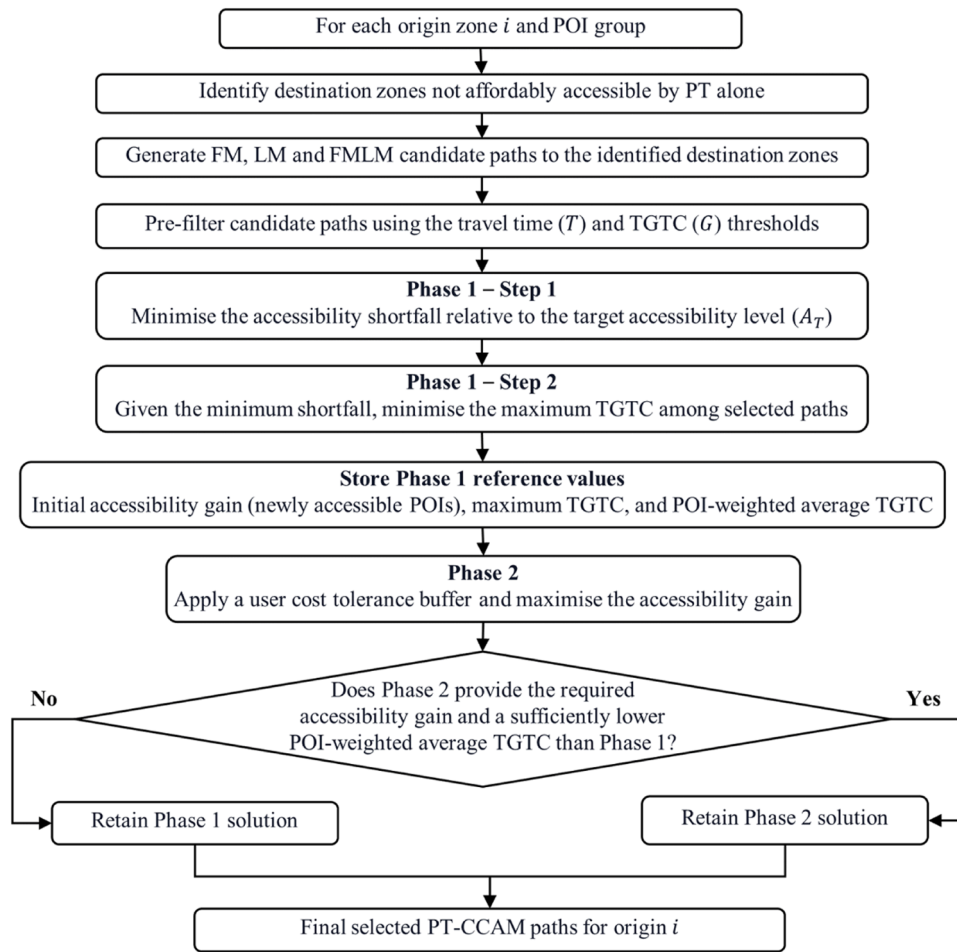


Fig. 2. Workflow of the two-phase PT-CCAM path-selection optimisation.

€0.10 lower than the Phase 1 value (recall that the user cost tolerance buffer, the minimum additional POI count and the required reduction in the POI-weighted average TGTC are policy parameters that may be adjusted according to local planning priorities).

Imagine that Phase 2 identifies an alternative path combination providing access to 30 additional POIs, with a maximum TGTC of €7.90 and a POI-weighted average TGTC of €6.95. All three conditions are satisfied: €7.90 is below the €8.14 ceiling, 30 exceeds the Phase 1 gain of 24 POIs, and €6.95 is at least €0.10 below €7.10. The Phase 2 solution is therefore retained. Had any of these conditions not been satisfied, the Phase 1 solution would have remained the final selected set of paths.

The complete optimisation model, including its phases, steps, notation, objective functions and constraints, is presented in [Appendix A](#).

As a final step, following PT-CCAM integration, equity is assessed by analysing the distribution of affordable accessibility before and after the intervention. This assessment draws on two complementary traditions of distributive justice that underpin transport equity research: an egalitarian perspective, concerned with the relative distribution of accessibility across socioeconomic groups, and a sufficientarian perspective, concerned with whether every zone attains a minimum acceptable level of accessibility, irrespective of how accessibility is distributed elsewhere ([Pereira et al., 2017](#); [Karner et al., 2025](#)). Three indices are adopted to jointly operationalise these perspectives, each capturing a distinct and complementary dimension of transport inequality and deprivation.

The Palma ratio ([Cobham & Sumner, 2014](#)) and the CCI ([Erreygers, 2009](#)) operationalise the egalitarian perspective. The Palma ratio compares average affordable accessibility between the top 10% and bottom 40% of zones ranked by income, capturing disparities between the most and least advantaged areas while addressing the Gini coefficient's

known insensitivity to changes at the extremes of the distribution. However, because it only compares averages at the tails of the income distribution, it disregards intermediate zones and does not show whether accessibility follows the socioeconomic ordering of zones across the full distribution. The CCI addresses this limitation by evaluating whether affordable accessibility is concentrated among higher- or lower-socioeconomic groups across the entire socioeconomic gradient ([Karner et al., 2025](#)). Unlike the standard concentration index from which it is derived, the CCI satisfies the transfer property, whereby the index registers a reduction in inequality when accessibility increases for a disadvantaged zone or decreases for a well-off zone, and an increase in inequality when the opposite occurs. It also normalises accessibility by its lower and upper bounds rather than by its mean, which is particularly suitable for the bounded CO measure adopted in this study ([Erreygers, 2009](#); [Karner et al., 2025](#)).

In contrast, the FGT index ([Foster et al., 1984](#)) operationalises the sufficientarian perspective by measuring the extent to which zones fall below a predefined accessibility threshold. Within the FGT family, FGT_0 measures only the extent of transport poverty as a headcount of zones falling below the threshold, while FGT_1 captures the average depth of the shortfall. This study adopts FGT_2 because it gives greater weight to deeper shortfalls and therefore jointly captures both the extent and severity of transport poverty ([Karner et al., 2025](#)). This makes FGT_2 particularly appropriate for an equity-focused framework whose objective is not only to reduce the number of underserved zones, but also to reduce the intensity of accessibility deprivation among the most disadvantaged PIAs. Its use is also consistent with recent European policy guidance, which lists FGT_2 as an example of a useful indicator for measuring transport poverty through accessibility deprivation

(European Commission, 2025).

Taken together, the three indices allow for a comprehensive pre- and post-intervention evaluation of both transport inequality and transport poverty.

4. Case study

The proposed methodology has been validated through its application to the city of Barcelona. The city was selected as a high-fidelity validation environment, offering a dense multimodal network and highly detailed transit, cost and spatial datasets with which to verify the framework's behavioural coherence before wider application. The most recent datasets available for each input were used; however, temporal differences between them should be considered when interpreting the results.

4.1. Barcelona city

Barcelona is a dense European city with a high-capacity PT network. According to the Àrea Metropolitana de Barcelona (AMB), the network reached a historic record of 818.42 million annual passenger journeys in 2025, comprising 479.91 million metro validations and 338.51 million metropolitan bus trips across directly and indirectly managed services (AMB, 2026). Beyond its strong PT performance, Barcelona has also hosted autonomous vehicle initiatives and automated mobility pilot projects (Gutiérrez, 2018; Renault Group, 2025). The city is therefore a suitable case study because it combines a dense, heavily used multimodal PT network with ongoing policy and operational interest in new mobility technologies.

In this application, CCAM solutions are modelled as shared CCAM shuttles (CS), functioning as integrated feeder services to the existing PT network. This choice aligns with sustainable mobility policies that aim to foster a modal shift from private cars towards shared transport systems (Gutiérrez, 2018; Transdev Nederland, n.d.).

The 73 neighbourhoods of Barcelona were selected as the fundamental spatial units of analysis. While finer resolutions like census tracts are standard, the neighbourhood level was chosen as the finest spatial unit for which all critical datasets were comprehensively available; this choice minimises the “scale effect” of the Modifiable Areal Unit Problem (MAUP) by ensuring data integrity without relying on artificial spatial disaggregation techniques. Furthermore, to mitigate the “aggregation (zone) effect”, population-weighted geometric centroids served as the representative origins and destinations for all trips. The population data used for this weighting were sourced at the urban block (manzana) level from the Barcelona City Council's urban planning dataset (Ajuntament de Barcelona, n.d.), a finer resolution than the neighbourhood level itself. This reduces the bias that would result from using simple geometric centroids, although the use of one representative point per neighbourhood remains a spatial simplification, particularly in larger or more internally heterogeneous neighbourhoods. While origins represented residential locations, destination centroids were linked to the specific POIs situated within each corresponding neighbourhood. POI data were obtained primarily from the Open Data portal of Barcelona City Council (Ajuntament de Barcelona, n.d.) and aggregated at the neighbourhood level. They were categorised into ten groups: cultural, educational, finance, food, healthcare, leisure, office, service, shopping and sport. These categories were selected to cover a broad range of daily and non-daily urban opportunities relevant to accessibility and equity assessment, consistent with proximity-oriented categorisations of urban opportunities (Silva et al., 2025). The datasets were first published in 2021 and are updated frequently; the versions used in this study were retrieved in 2025. The PT network was modelled using 2024 General Transit Feed Specification (GTFS) data sourced from the Mobility Database (The Mobility Database, 2024). The data include metro, urban bus, metropolitan bus, tram and suburban rail services. OpenStreetMap (OpenStreetMap contributors, n.d.) data sourced from BBBike were used

to model the walkable and drivable road network (BBBike, 2025). Fig. 3 shows Barcelona's study area, rail network, and rail station locations. Finally, six datasets were incorporated to assess socioeconomic disparities, covering income, car ownership, employment, education, migration background, and disability.

The first step involved computing detailed PT itineraries between all OD pairs using the r5r routing engine (Pereira et al., 2021) for a representative weekday morning peak period (08:00-09:00). Travel times were computed for departures sampled at 1-minute intervals across this window, and the median (50th percentile) value across these departures was retained for each OD pair. This approach reduces the sensitivity of the reported accessibility values to short-term fluctuations in PT service frequency and scheduling within the morning peak (Conway et al., 2018; Pereira et al., 2024). To ensure behavioural realism, several constraints were imposed on the routing algorithm: a maximum walking duration of 10 minutes (Pérez Sans et al., 2025); a maximum total trip duration of 60 minutes; and a walking speed of 3.6 km/h (Pereira et al., 2024). In the baseline PT routing, 4,978 of the 5,256 possible interzonal OD pairs produced an itinerary under these routing constraints, while 278 OD pairs (5.29%) did not.

At this stage, only detailed itineraries were generated, including IVT, WT, WkT, NT, and modal sequences. No accessibility or cost indicators were calculated during the routing step. Instead, these itinerary outputs were subsequently used to compute TGTC and CO-based accessibility measures, based on the parameter specifications described in the following section.

4.2. TGTC parameters and affordable accessibility thresholds

To ensure methodological robustness and empirical consistency, the TGTC parameters were derived through a structured review of the academic literature, official statistics, regulatory frameworks, and operational evidence.

First, speed assumptions were defined to reflect realistic urban operating conditions. Walking speed was set to 3.6 km/h (Pereira et al., 2024). IVT_{PT} was derived from GTFS schedules to reflect actual service operations. For CS, three operating speeds were tested (30, 20, and 15 km/h) to represent different levels of technological maturity and regulatory constraints. The 30 km/h value reflects the speed limit applied across Barcelona's secondary street network since 2020 (Ajuntament de

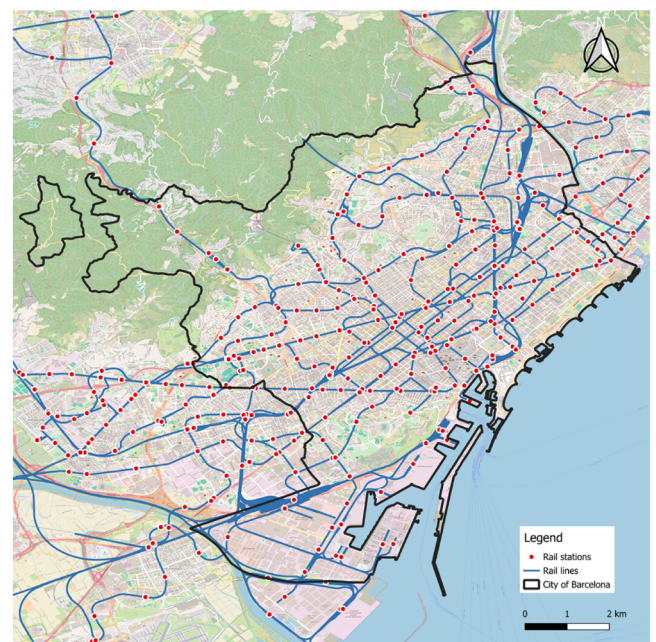


Fig. 3. Barcelona, study area, rail network and rail stations.

Barcelona, 2020), while lower values reflect evidence from initial pilot deployments such as the ÈRICA shuttle operating at approximately 18 km/h (Gutiérrez, 2018).

Second, fare and riding cost parameters were defined. Walking was assumed to involve no direct monetary cost. For PT, a flat fare of €2.90 was adopted, corresponding to the single-journey ticket price for Barcelona's fare ring 1 established by the Autoritat del Transport Metropolità (ATM, 2026). No time-based or distance-based PT riding cost was applied. Alternative fare structures used by a small minority of operators were omitted for simplicity. For CS, riding costs were derived from benchmark estimates of USD 0.50-1.00 per vehicle-mile for SAVs (Litman, 2025). Adopting a mid-range value of USD 0.75 per mile yields an approximate cost of €0.43 per km after unit and currency conversion.

Third, VoT for car and PT was derived from the meta-analysis of Wardman et al. (2016) and updated from 2010 to 2023 using the income-elasticity adjustment embedded in their model to reflect current socioeconomic conditions in Catalonia. Given the speed limits applied in the routing framework, only free-flow VoT values were considered. The resulting commuting VoT values were €11.83/h for car and €9.02/h for PT.

Empirical evidence on VoT in autonomous vehicles indicates heterogeneous effects, with substantial reductions (30-40%) reported for privately owned AVs but more modest changes for shared services (Steck et al., 2018; Kolarova et al., 2019; de Almeida Correia et al., 2019; Rashidi et al., 2020; Zhong et al., 2020). Given that CS operate as shared, low-speed complementary services integrated with PT, a moderate VoT reduction was adopted. Specifically, VoT_{CS} was set at 75% of VoT_{car} , corresponding to €8.87/h.

Walking and waiting time were valued more highly than IVT, consistent with extensive empirical evidence (Wardman, 2004; Wardman et al., 2016; Litman, 2023). Reported penalties typically range between $1.6-2.4 \times IVT$ for walking and $2.4-3.5 \times IVT$ for waiting, with appraisal guidance recommending values around 200-250% of IVT. Based on this convergence across revealed and stated preference studies, $\alpha = 2.0$ was adopted for waiting and $\beta = 2.5$ for walking.

Finally, transfers impose additional burdens beyond IVT, including uncertainty and wayfinding effort (Wardman, 2014; Yap et al., 2024). These studies show that interchange penalties exceed standard out-of-vehicle valuations and vary by transfer type. Accordingly, a transfer multiplier of $\gamma = 2.0$ is applied to IVT_{PT} . In addition, fixed interchange penalties expressed in IVT-equivalent minutes are introduced, ranging from 4-5 minutes for simple same-mode transfers, around 6 minutes for car-PT transfers, and up to 8 minutes for transfers between different PT modes requiring significant vertical movement, longer walking distances, or greater interchange complexity.

A summary of the parameters used to calculate TGTC from the detailed itineraries is provided in Table 1.

After calculating travel times and TGTC values and establishing the framework for the affordable accessibility assessment, this study defined accessibility time thresholds for the different POI groups. These were defined by synthesising global normative standards for proximity-oriented accessibility, inspired by Silva et al. (2025), with empirical travel behaviour data derived from the Barcelona EMEF survey (Pérez Sans et al., 2025). A 10-minute threshold was assigned to the food category, reflecting the high frequency and essential nature of these trips. A 15-minute threshold was applied to education (specifically

primary and pre-primary levels), healthcare (primary care and pharmacies), and leisure amenities. Furthermore, a 20-minute threshold was adopted for more spatially dispersed or specialised activities, encompassing cultural venues, finance, offices, service companies, shopping centres, and sport facilities. Ultimately, these thresholds were set to reflect both observed travel patterns and broader proximity-based planning goals. The adopted time thresholds refer to total door-to-door journey times, which in practice comprise both walking and PT components. For shorter thresholds, such as 10 minutes, walking may represent a relatively larger share of the total travel time, particularly for nearby destinations. Nevertheless, PT-CS integration is intended primarily to extend access to more distant destinations by improving PT connectivity, rather than to serve nearby zones that may already be reachable on foot.

In addition to the time-based criteria, a uniform TGTC threshold was applied across all activity types, following the wage-based affordability benchmarking approach proposed by El-Geneidy et al. (2016), which links travel cost to earning capacity. Based on official 2023 statistics (Idescat, 2023a), the average gross hourly wage in Catalonia is approximately €19/h (€19.89/h for men and €18.05/h for women). To adopt a conservative and equity-sensitive reference value, €18/h was used as the benchmark. Setting the affordability threshold at half of this hourly wage assumes that a single trip should not exceed the equivalent of 30 minutes of labour income, resulting in a TGTC limit of €9.

Section 5.5 expands on threshold choices by presenting a sensitivity analysis in which the key ones have been varied. It should be noted, however, that the thresholds adopted in this case study are intended as city-wide planning references for the Barcelona context and should not be interpreted as universally transferable. That is, although the methodological framework can be applied to different cities and population groups, tolerable travel-time and TGTC thresholds should be recalibrated according to the urban context, transport system, fare structure and characteristics of the target population.

4.3. Socioeconomic indicators

To conduct the vulnerability analysis, a targeted set of neighbourhood-level socioeconomic indicators was selected. Household disposable income per capita, employment rates, the population with low educational attainment, and the share of residents from low- or middle-income countries were derived from Idescat (2023b). Following Idescat's bivariate analysis methodology, these indicators were retained based on their statistical significance and low intercorrelation, ensuring that the selection captures essential socioeconomic dimensions without introducing redundant information (Idescat, 2021).

In addition, the motorisation index and the proportion of people with legally recognised disabilities were included to reflect transport-related dependency and functional mobility needs. These data were obtained from the Open Data portal of the Barcelona City Council (Ajuntament de Barcelona, n.d.). A detailed summary of the selected variables and their definitions is provided in Table 2.

To assess vulnerability spatially, each indicator was evaluated across Barcelona's neighbourhoods using a quartile-based classification. A neighbourhood was classified as socioeconomically vulnerable if it fell within the most disadvantaged quartile for even just one indicator. PIAs were then identified as zones that simultaneously exhibited both high

Table 1
Default parameters for the TGTC calculation.

Mode	Speed (km/h)	Fare		VoT				Transfer
		F (€)	RC (€/km)	IVT (€/h)	α	β	γ	TT (min)
Walk	3.6	0	0	0	2	2.5	2	Between 4 and 8 depending on the interchange type
PT	Based on the GTFS	2.90	0	9.02				
CS	Limited to: 30 / 20 / 15	0	0.43	8.87				

Table 2
Summary of socioeconomic indicators used for the vulnerability assessment.

Indicator (year)	Description
Household disposable income per capita (2022)	The net financial resources available to households for consumption or saving (wages and benefits minus taxes), indicating baseline economic vulnerability.
Employed population (2022)	The percentage of residents aged 20-64 formally registered with Social Security, reflecting labour market attachment and economic stability.
Population with low education (2022)	The share of residents aged 20 or over who are illiterate or have attained at most primary education, representing limited human capital and increased exposure to social exclusion.
Foreigners from low- or middle-income countries (2022)	The percentage of residents holding the nationality of low- or middle-income countries (World Bank classification), capturing populations potentially facing financial or linguistic barriers.
Motorisation index (2023)	The number of privately owned vehicles per thousand inhabitants, serving as a proxy for car ownership and access to private mobility.
People with legally recognised disabilities (2019)	The number of residents with officially recognised disabilities, identifying populations with higher dependency on accessible and specialised transport solutions.

socioeconomic vulnerability and low PT-only affordable accessibility.

5. Results

This section presents the results of the proposed framework, beginning with the baseline assessment of PT-only affordable accessibility and progressing to the optimisation of PT-CCAM integration and its associated equity outcomes.

5.1. Affordable accessibility assessment

After defining the routing parameters, VoT assumptions, fare structures, and the time and TGTC thresholds, the affordable accessibility assessment was conducted. Using the TGTC formulation and activity-specific time limits, accessibility levels were computed for all zones and POI groups under baseline PT conditions.

To visualise the relationship between accessibility and travel time or monetary cost, an approach inspired by Access Profile Analysis (APA) was employed (Neudorf, 2014; Abdelwahab et al., 2021). In its conventional form, APA represents accessibility by plotting the cumulative number of reachable destinations along a continuous travel time axis or, alternatively, along a cost axis. These profiles illustrate how opportunities progressively accumulate as temporal or financial constraints are relaxed, providing an intuitive representation of transport performance.

In the present affordable accessibility framework, APA is extended into a joint time-cost space. Because accessibility is defined by the simultaneous satisfaction of both travel time and TGTC thresholds, the visualisation requires a three-dimensional representation. As shown in Fig. 4, the horizontal axes represent travel time and TGTC, while the vertical axis captures the cumulative number of accessible POIs through PT.

The resulting surface, illustrated as an example for Zone 57 and healthcare accessibility, shows how accessible opportunities accumulate only within feasible regions of the time-cost plane. At low levels of time and TGTC, accessibility remains minimal, reflecting strict constraints. As either dimension gradually expands, more destinations become reachable; however, the steepest increases occur where both constraints are simultaneously relaxed. The colour gradient further highlights this progression, with red indicating low accessibility and green representing higher CO levels.

The results of PT-only affordable accessibility are presented in Fig. 5 for four representative activity types: food, healthcare, shopping, and sport. The maps reveal a clear spatial gradient, with central

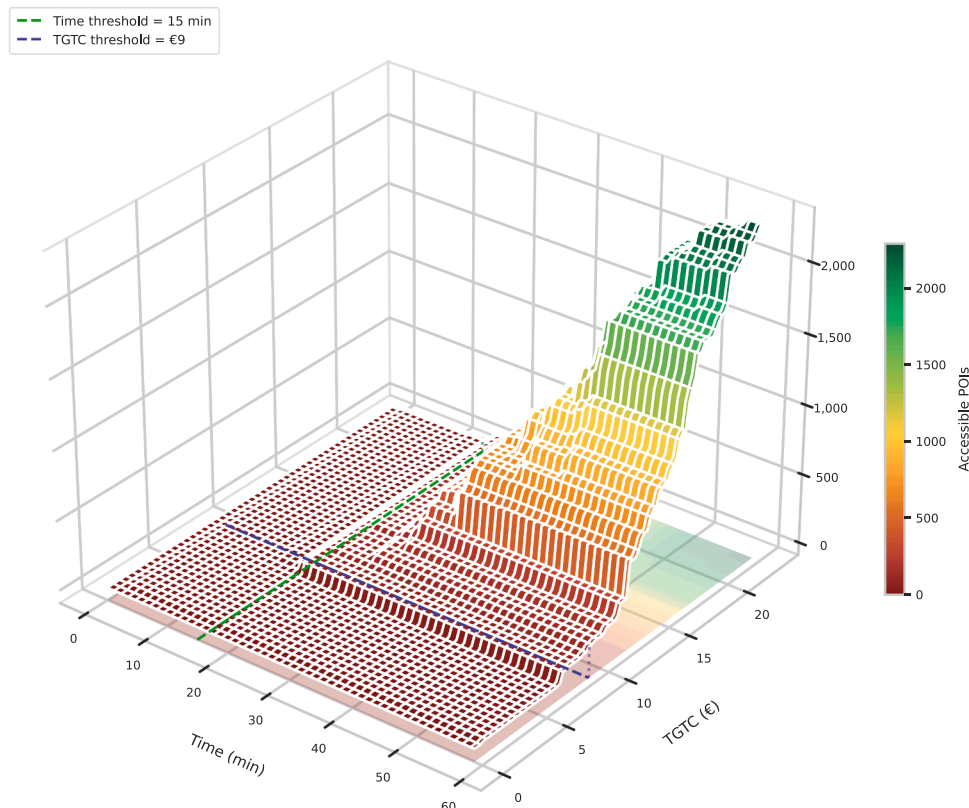


Fig. 4. APA of affordable accessibility in time-cost space.

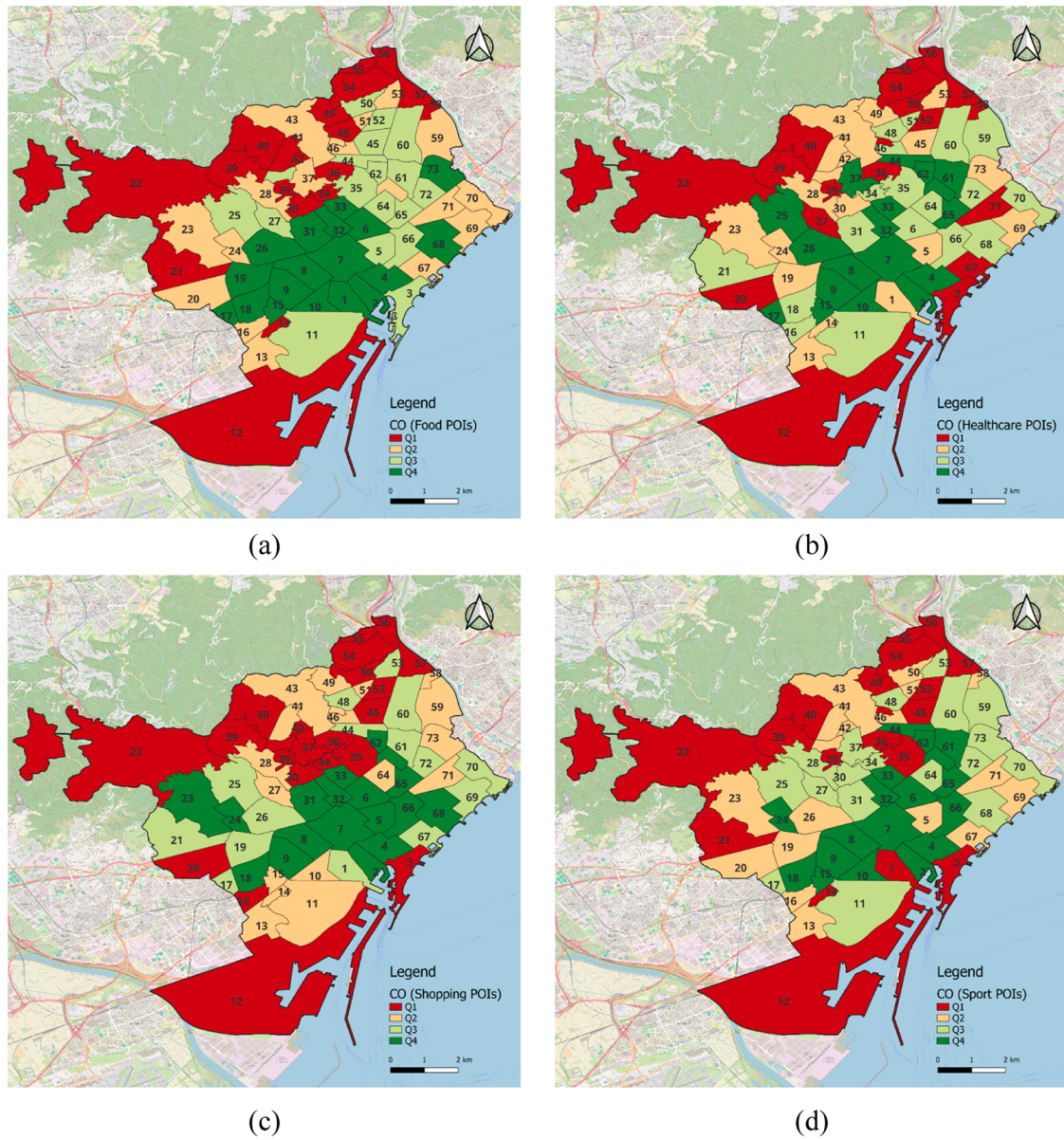


Fig. 5. Current PT-only affordable accessibility levels to (a) food, (b) healthcare, (c) shopping, and (d) sport POIs.

neighbourhoods displaying higher PT-only affordable accessibility levels (upper statistical quartiles, Q₃ and Q₄), while peripheral areas, particularly in the northern, north-western, and southern parts of the city, show considerably lower values (i.e., Q₁ and Q₂). This pattern reflects the concentration of services and stronger PT connectivity in central zones.

Following the assessment of baseline PT affordable accessibility, neighbourhoods with low levels of access are identified by considering the activity-specific median value of PT-only accessibility across Barcelona as the reference threshold. The median represents the typical performance of the PT system and provides a balanced benchmark for distinguishing relatively underserved areas from the rest of the city. Neighbourhoods with accessibility levels below this median threshold are classified as low-access areas and considered for further vulnerability screening.

5.2. Vulnerability analysis

The vulnerability analysis was conducted by identifying socially vulnerable zones and intersecting them with low-access areas. Fig. 6(a)

illustrates the socially vulnerable zones, shown in red, representing neighbourhoods that fall within the most disadvantaged quartile for at least one socioeconomic indicator. Overall, 44 of the 73 neighbourhoods (approximately 60%) were classified as socially vulnerable. Building on this vulnerability classification, Figs. 6(b)–6(e) present the resulting PIAs, shown in red, for food, healthcare, shopping, and sport POIs, respectively. These PIAs represent the intersection of the socioeconomic disadvantage shown in Fig. 6(a) with the specific PT-only affordable accessibility gaps identified for each POI group. Consequently, these zones are designated as the focus for PT-CCAM integration (i.e., PIAs).

5.3. PT-CS integration

Once PIAs are identified, CS services are integrated with PT in these zones. As previously specified, FM, LM, and FMLM CS configurations are each evaluated under operating speeds of 15, 20, and 30 km/h. A maximum feeder time of 10 minutes is adopted, consistent with average walking durations reported by the Autoritat del Transport Metropolità (ATM) for Barcelona (Pérez Sans et al., 2025), reflecting typical access and egress tolerances.

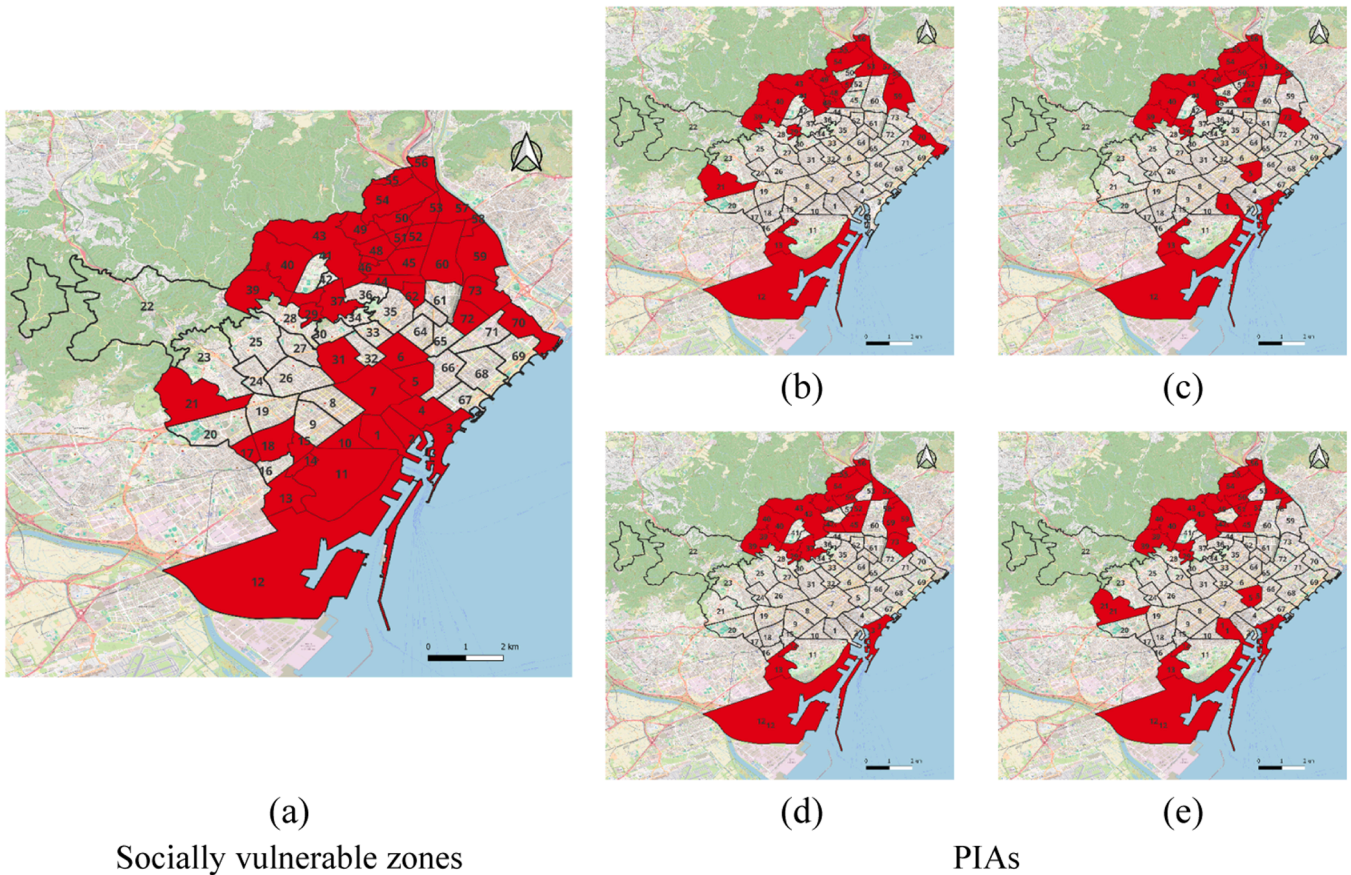


Fig. 6. Vulnerability assessment maps showing (a) socially vulnerable zones; PIAs for (b) food, (c) healthcare, (d) shopping, and (e) sport. The numbers displayed within each zone are identifiers used to label Barcelona's 73 neighbourhoods and do not represent accessibility, vulnerability, or POI-count values.

Using *r5r* multimodal routing, a comprehensive search space of feasible paths was generated for each integration configuration. All PT stops included in the GTFS files were considered as potential integration points, rather than being restricted to a predefined subset of particular modes. Under the FM configuration, a 10-minute threshold was applied between origins and the nearest PT stops, and the routing engine identified the fastest feeder-PT combinations that ensured a feasible temporal connection between feeder arrival and PT departure. The LM configuration applied the same 10-minute constraint at the destination end. For the FMLM configuration, the available feeder time was split equally, with five minutes allocated to both the origin and destination ends. In all cases, only temporally integrated paths, where feeder and PT schedules aligned without violating time constraints, were retained to form the pool of candidates for the subsequent optimisation stage.

In the optimisation stage, the optimal configuration of PT-CS paths within this pool was identified for each PIA. This process was implemented using the Google OR-Tools linear solver (Google, n.d.). For an origin within a PIA, all feasible multimodal routes were evaluated by the solver to determine the specific combination required to reach the target accessibility level (A_T). This target was defined as the median PT-only accessibility value across the respective POI groups, ensuring that PIAs were elevated to a representative city-wide performance standard.

As explained in detail in Section 3, the optimisation follows a two-phase structure. In Phase 1, the model seeks to close the accessibility gap while minimising the maximum TGTC among selected paths. In Phase 2, a user cost tolerance buffer of 10% ($b = 0.1$) is applied relative to the baseline maximum TGTC, allowing limited flexibility in individual travel costs if this yields meaningful accessibility gains. To prevent unjustified cost increases, the solution of Phase 2 is accepted only if it provides at least one additional POI (i.e., $\Delta A_g = 1$) and reduces the

POI-weighted average TGTC by at least €0.1 (i.e., $\Delta W = 0.10$ €).

A subset of the optimisation-based integration outcomes for healthcare POIs is presented in Table 3, illustrating representative examples of the selected PT-CS paths and their associated configurations. For the sample PIAs, the table reports the corresponding destination zone and the integration mode (FM, LM, or FMLM) with the specified operating speed. It compares baseline PT-only travel time and TGTC with integrated PT-CS travel time and TGTC, and additionally provides the number of transfers (i.e., NT).

Among Barcelona's 73 neighbourhoods, Zone 57 (La Trinitat Vella) was deliberately selected as an illustrative example because it is identified as a PIA across all ten POI categories considered in this study. It is a peripheral, socioeconomically vulnerable neighbourhood in the Sant Andreu district, situated at the north-eastern edge of the city. As a representative example, Fig. 7 illustrates the impact of PT-CS integration on healthcare accessibility for PIA 57. Each labelled marker represents a destination neighbourhood, with the label showing its ID and the bubble size proportional to the number of healthcare POIs available in that

Table 3

Detailed path-level characteristics of selected PT-CS integrations for healthcare accessibility.

PIA ID	Destination ID	PT only		PT-CS integration			
		Time (min)	TGTC (€)	Time (min)	TGTC (€)	NT	Integration mode
39	29	24.2	13.2	8.5	8.5	2	FMLM (20 km/h)
40	28	18.5	10.7	10.7	7.4	1	FM (30 km/h)
45	62	16.0	9.9	9.4	6.7	1	LM (20 km/h)
57	60	17.1	6.7	13.3	8.0	1	FM (15 km/h)

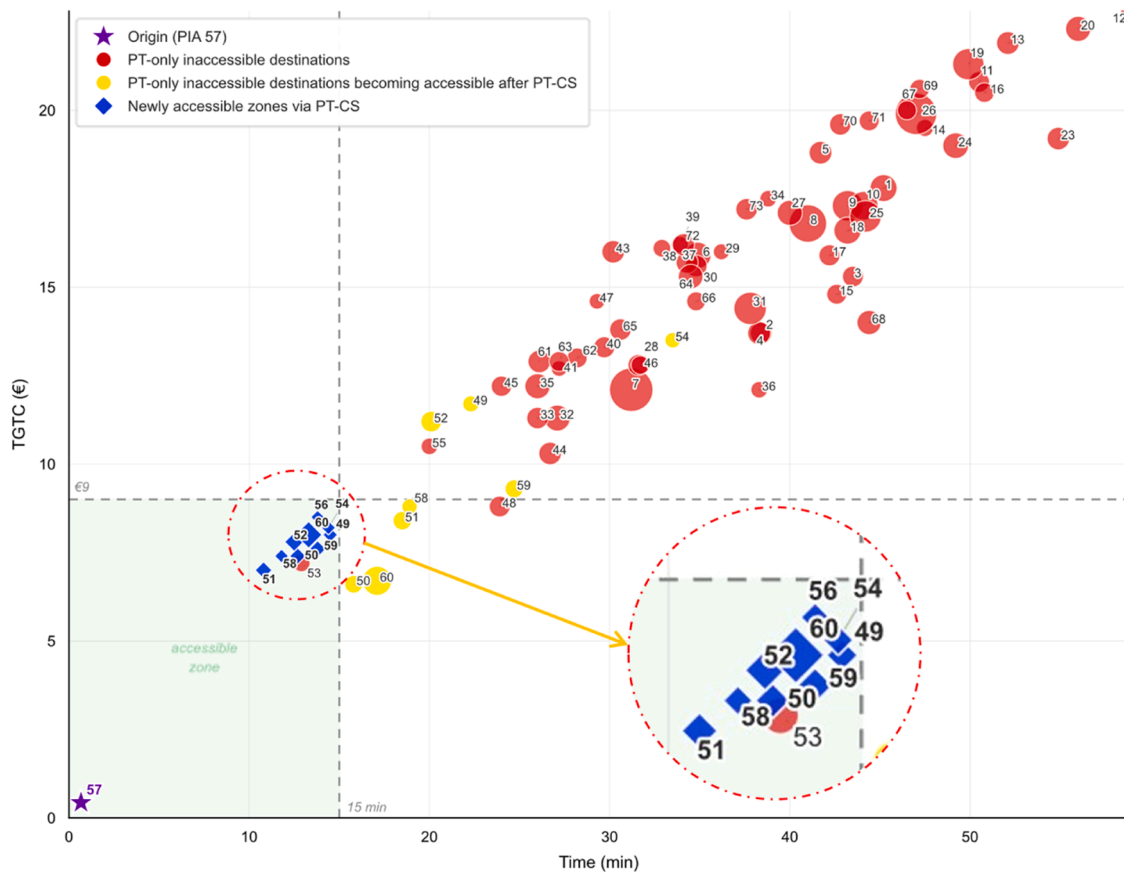


Fig. 7. Impact of PT-CS integration on healthcare accessibility for PIA 57.

zone. The dashed vertical and horizontal lines denote the travel time and TGTC thresholds, respectively, so that only destinations located within the lower-left green-shaded area are considered affordably accessible. Under the PT-only scenario, both the red and yellow circles represent destination zones that were located outside the feasible region and therefore did not satisfy the affordable accessibility criteria. However, the yellow circles identify those destinations that became accessible after PT-CS integration. Their updated travel time and TGTC values are shown by the corresponding blue diamonds, which fall within the feasible accessibility region. Specifically, nine zones that were previously outside the thresholds were brought within both constraints through the selected PT-CS connections. As a result, the total number of accessible healthcare POIs increased from 17 to 156.

The integration outcomes across POI groups are summarised in Table 4. Overall, the results show that nearly every PIA across all POI categories obtained at least one newly accessible destination through

PT-CS integration wherever integration was feasible. Across most POI groups, the close match between successfully integrated zones and PIAs indicates that nearly all PIAs gained at least one new PT-CS path. An exception is observed in the food POI group. Out of the 21 identified PIAs, PT-CS integration was successful in only 14. This comparatively lower rate can be explained by the strict 10-minute travel time threshold applied to food accessibility. While the TGTC threshold (i.e., €9) is uniform across all POI groups, the presence of food-related POIs in all zones makes the temporal constraint particularly restrictive for this category.

To provide an overall synthesis across all POI groups and to generalise beyond differences in CS operating speeds, the aggregated optimisation outcomes are presented in Table 5. The table summarises the integration results at the city-wide level, abstracting from activity-specific variations and offering a comprehensive overview of the scale, configuration, and intensity of PT-CS deployment.

Under this aggregated perspective, a total of 34 PIAs were identified as candidates for integration. For all 34 zones, at least one feasible PT-CS

Table 4
Summary of PT-CS integration outcomes across POI groups.

POI category	Number of PIAs	Number of PIAs with successful PT-CS integration	Average number of paths per PIA
Cultural	22	22	4
Education	23	23	2.5
Finance	26	26	2.9
Food	21	14	1.4
Healthcare	23	23	2.5
Leisure	26	25	2.8
Office	28	27	4
Service	21	20	1.6
Shopping	23	23	2.4
Sport	24	24	4

Table 5
City-wide summary of selected PT-CS integration paths.

Indicator	Value
Total candidate PIAs	34
Zones with at least one selected PT-CS path	34 (100%)
Distribution of integration types	
FM	60.18%
LM	36.72%
FMLM	3.10%
Number of selected paths per zone	
Mean	6.65
Median	5
Standard deviation	4.47

path was identified as affordably accessible. The distribution of integration types shows that FM configurations account for 60.18% of the selected paths, followed by LM configurations at 36.72%, while FMLM solutions represent only 3.10%.

5.4. Equity assessment

Following the accessibility and integration analysis, the performance of the PT-CS framework is evaluated from both efficiency and equity perspectives.

Table 6 presents the results of the affordable accessibility analysis under the median target accessibility. The PT-only median accessibility is compared with the PT-CS enhanced median accessibility, illustrating how CS integration expands the number of opportunities that can be reached within acceptable time and cost limits.

Overall, the results indicate an average accessibility increase of approximately 18.1%, demonstrating that PT-CS integration can meaningfully improve access to essential opportunities while preserving both temporal efficiency and affordability.

Table 7 summarises the equity impacts resulting from the PT-CS integration. Overall, the findings indicate substantial and consistent improvements across almost all POI groups. Note that equity is represented by values near 1 for the Palma ratio and near 0 for CCI and FGT₂. The relative change column is calculated accordingly, such that positive values indicate a shift towards a more equitable distribution of accessibility, while negative values indicate a shift away from it. Therefore, the sign does not simply represent an increase or decrease in the raw index value, but whether the outcome represents an improvement or deterioration from an equity perspective.

The Palma ratio decreased by an average of approximately 13.6%, indicating a narrowing of the accessibility gap between the most advantaged (top 10%) and least advantaged (bottom 40%) income groups. An exception is observed for the cultural and food POI groups, where the Palma ratio slightly worsened.

The CCI and FGT₂ indicators show strong positive relative improvements, averaging 38.8% and 57.6%, respectively. It is important to note that these indices capture distinct equity dimensions. The CCI is ranked according to socioeconomic status; therefore, a positive relative change indicates that accessibility is being redistributed along the socioeconomic gradient towards more disadvantaged zones. In contrast, FGT₂ is a population-weighted measure of accessibility ‘severity’ or ‘intensity.’ It quantifies the squared shortfall of accessibility relative to the defined target threshold. Consequently, improvements in CCI indicate a more favourable distribution towards lower-income zones, while the substantial positive relative change in FGT₂ reflects a significant decline in the depth and severity of accessibility gaps across the PIAs.

Overall, equity indices demonstrate a consistent improvement across the POI groups. These results confirm that PT-CS integration enhances both socioeconomic fairness (Palma and CCI) and the mitigation of extreme deprivation (FGT₂). By narrowing the gap between the most

and least advantaged neighbourhoods and reducing the depth of accessibility shortfalls, the framework effectively fosters a more inclusive and balanced urban structure. These distributional patterns of the three indices are visually illustrated in Fig. 8, which compares the pre- and post-integration values of the Palma ratio, CCI, and FGT₂ across POI groups, highlighting both the magnitude and direction of equity changes relative to their ideal benchmarks.

5.5. Sensitivity analysis

It is important to note that, while the methodological framework proposed in Section 3 is transferable (e.g., for use in different cities or in rural or peripheral areas of different sizes) and adaptable (e.g., to include different existing transport modes or to focus on the accessibility needs of specific target groups), it requires several case-specific parameters to be determined and calibrated for each application. These include, for example, speed limits, fare structures for both PT and CS, and tolerable travel time and TGTC thresholds.

Therefore, the sensitivity analysis reported in Table 8 focuses on three parameters that directly influence affordable PT-CS accessibility in this case study: the travel time threshold, the TGTC threshold, and the fixed CS base fare, F_{CS} . The purpose is not to identify universally correct threshold values, but to test whether the main case-specific findings remain stable under alternative planning assumptions.

Several scenarios were tested by varying these parameters. The first group examined uniform time thresholds of 10, 15, 20 and 30 minutes across all POI categories, replacing the survey-based activity-specific thresholds. The maximum CS feeder duration was kept fixed at 10 minutes for FM and LM and at 5 + 5 minutes for FMLM across all sensitivity scenarios. As shown in Table 8, the number of PIAs changed only moderately across these scenarios because, in the absence of universally accepted standards, PIA identification is partly based on relative criteria, including the city-wide median accessibility benchmark and the vulnerability classification. Under stricter thresholds, baseline PT-only accessibility is lower, so successful PT-CS connections can produce larger proportional gains. However, the feasibility of PT-CS integration is more sensitive to strict time limits. Under the 10-minute threshold, only 22 of the 33 PIAs were successfully integrated, and the average number of paths per PIA fell to 1.50. This indicates that very strict proximity-based standards may identify more accessibility gaps while leaving limited scope for PT-CS solutions to close them. Even though CO improvement did not increase monotonically as the time threshold was relaxed, more destinations were already reachable by PT alone under the less restrictive thresholds, reducing the marginal contribution of PT-CS integration. Therefore, lower relative improvements under relaxed thresholds should not be interpreted as weaker performance, but rather as the result of a less restrictive baseline condition.

All tested time-threshold scenarios produced more equitable post-integration outcomes. However, the magnitude of improvement varied: gains ranged from 7.79% to 12.78% for the Palma Ratio, from 31.66% to 53.55% for the CCI, and from 32.9% to 59.57% for FGT₂ (recall that a positive relative change indicates greater equity relative to the PT-only baseline). The 10-minute scenario produced the smallest FGT₂ improvement, coinciding with successful PT-CS integration in only 22 of the 33 PIAs. Therefore, all tested time thresholds produced equity gains, although the magnitude of those gains was sensitive to the selected threshold.

The second group of scenarios varied the initial €9 TGTC threshold, representing stricter and more relaxed affordability conditions. As expected, the results showed that PT-CS integration was particularly sensitive to strict affordability assumptions. At the €4.50 threshold, no feasible PT-CS integration was identified, despite 36 PIAs being detected. This suggests that, under very strict affordability requirements, PT-CS integration may require fare integration, subsidies or lower user charges to remain viable. When the TGTC threshold was relaxed, the accessibility target could be reached for all PIAs, although the relative

Table 6

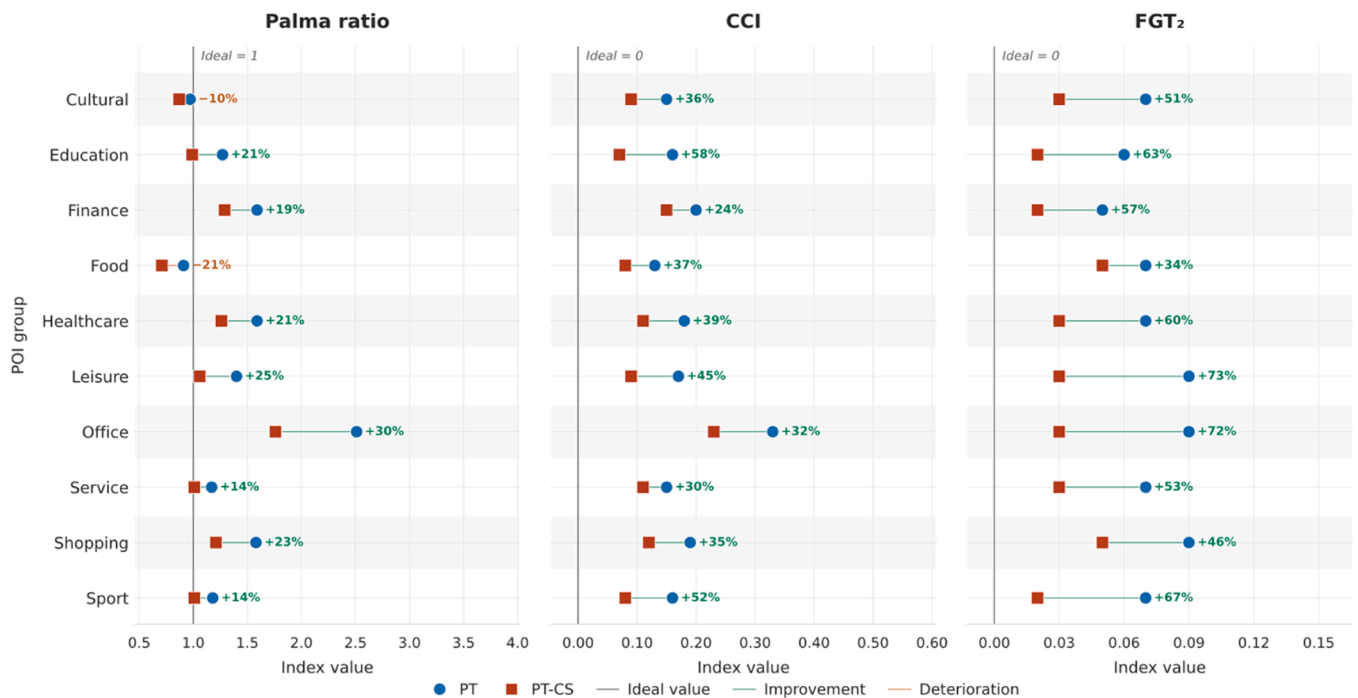
Median affordable accessibility outcomes before and after PT-CS integration.

POI group	CO (POI count)		
	PT-only median	PT-CS median	Relative increase (%)
Cultural	240	265	10.42
Education	105	119	13.33
Finance	87	110	26.44
Food	136	173	27.21
Healthcare	82	98	19.51
Leisure	16	19	18.75
Office	264	327	23.86
Service	4	5	25.00
Shopping	13	14	7.69
Sport	397	432	8.82
			Average: +18.1

Table 7

Equity impacts of affordable accessible PT-CS integration.

POI group	Palma ratio			CCI			FGT ₂		
	PT	PT-CS	relative change (%)	PT	PT-CS	relative change (%)	PT	PT-CS	relative change (%)
Cultural	0.97	0.87	-10	0.15	0.09	36	0.07	0.03	51
Education	1.27	0.99	21	0.16	0.07	58	0.06	0.02	63
Finance	1.59	1.29	19	0.2	0.15	24	0.05	0.02	57
Food	0.91	0.71	-21	0.13	0.08	37	0.07	0.05	34
Healthcare	1.59	1.26	21	0.18	0.11	39	0.07	0.03	60
Leisure	1.4	1.06	25	0.17	0.09	45	0.09	0.03	73
Office	2.51	1.76	30	0.33	0.23	32	0.09	0.03	72
Service	1.17	1.01	14	0.15	0.11	30	0.07	0.03	53
Shopping	1.58	1.21	23	0.19	0.12	35	0.09	0.05	46
Sport	1.18	1.01	14	0.16	0.08	52	0.07	0.02	67
Average:			+13.6	Average:		+38.8	Average:		+57.6

**Fig. 8.** Equity indices before and after affordable accessible PT-CS integration.**Table 8**

Sensitivity of PIA identification, PT-CS integration and equity outcomes to the travel time threshold, TGTC threshold and fixed CS base fare.

Scenario	T (min)	G (€)	F _{CS} (€)	Total number of PIAs	Number of PIAs with successful PT-CS integration	Avg. number of paths per PIA	Avg. CO Δ (%)	Avg. Palma ratio Δ (%)	Avg. CCI Δ (%)	Avg. FGT ₂ Δ (%)
Baseline	activity-specific	9	0	34	34	6.65	18.1	13.6	38.8	57.6
T10	10	9	0	33	22	1.5	22.73	10.89	47.9	32.9
T15	15	9	0	35	35	4.14	20.95	7.79	53.55	58.14
T20	20	9	0	31	31	6.65	15.98	12.46	34.73	59.57
T30	30	9	0	31	31	7.16	9.92	12.78	31.66	47.41
G4.5	activity-specific	4.5	0	36	0	N/A	0	0	0	0
G13.5	activity-specific	13.5	0	34	34	8.85	15.56	8.07	53.37	59.97
G18	activity-specific	18	0	34	34	8.94	15.56	8.11	53.46	59.95
F _{CS} 0.5	activity-specific	9	0.5	34	34	5.56	17.22	11.49	32.31	55.01
F _{CS} 1.0	activity-specific	9	1	34	34	4.65	12.43	8.85	25.76	49.51

CO improvement did not necessarily increase. This occurred because a higher TGTC threshold also increased baseline PT-only accessibility,

reducing the marginal gain attributable to PT-CS. As in the time-threshold scenarios, all feasible TGTC-threshold scenarios produced more equitable post-integration outcomes across the three equity indicators, although the magnitude of the gains varied. The exception was the strictest TGTC threshold of €4.50, under which no feasible integration was identified and, consequently, no equity gain was recorded. Under the relaxed thresholds, all three indicators continued to show equity improvements, although the magnitude of the gains differed: improvements were smaller for the Palma ratio but larger for the CCI and FGT₂. The almost identical results obtained under the two relaxed thresholds suggest that further relaxation beyond €13.50 had little additional effect on equity outcomes.

The third group of scenarios tested the effect of introducing fixed CS base fare values, F_{CS} , of €0.50 and €1.00 in addition to the distance-based fare. As shown in Table 8, all PIAs remained successfully integrated under these fare scenarios, but the number of feasible paths per PIA decreased as F_{CS} increased because of the affordability threshold. The average CO improvement also declined. The equity indicators followed the same pattern as in the previous groups, remaining positive under both fare scenarios, although the magnitude of the gains declined consistently as F_{CS} increased. Unlike in the relaxed TGTC scenarios, introducing a fixed boarding charge reduced the gains across all three equity indicators simultaneously. The mode distribution nevertheless remained broadly stable: FM stayed dominant at approximately 60%, followed by LM at around 40%. FMLM, which accounted for only 3.10% of the baseline solutions, was no longer selected once a fixed base fare was introduced, because it includes two CS legs and therefore incurs the fixed charge twice, making the simpler FM or LM alternatives, where available, less costly.

Overall, the sensitivity analysis shows that targeted PT-CS integration generally improved affordable accessibility and equity, although the tested parameters had different effects. Very strict time thresholds affected integration feasibility and the magnitude of the improvements, particularly at 10 minutes. The strictest TGTC threshold eliminated feasible integration altogether, while higher fixed CS fares reduced the number of feasible paths and weakened both accessibility and equity gains. Moreover, relaxing the TGTC threshold beyond €13.50 produced little additional change. Affordability therefore emerged as the more binding constraint under the tested conditions. This pattern is consistent with Barcelona's compact, service-dense structure, where cost constraints appear more restrictive than travel-time constraints.

6. Discussion

Automation alone does not guarantee equitable mobility. Although CCAM technologies can expand physical reachability, their societal value depends fundamentally on how they are integrated within existing transport systems and pricing structures. In this study, PT-CCAM strategic integration is framed around a clear objective: strengthening equitable mobility by enabling vulnerable populations to gain meaningful and economically viable access to essential opportunities.

A central contribution of the study lies in moving beyond travel time as the sole indicator of accessibility performance and, more importantly, in treating affordable accessibility itself as the optimisation objective rather than an ex-post evaluation metric. Time-based measures often portray feeder-based automation as uniformly beneficial, since additional connections shorten trips and expand network reach. However, the Barcelona results demonstrate that temporal improvements alone may obscure important distributional consequences. In several neighbourhoods, PT-CCAM options reduced travel time but exceeded the affordability benchmark and were therefore excluded from the feasible solution set. Improved temporal performance may thus coincide with increased economic burden. The interaction between PT and CCAM is therefore conditional on fare structures and on the composition of generalised travel cost. When pricing surpasses affordability thresholds, integration may remain technically feasible yet socially exclusionary.

Affordable accessibility functions here as both an evaluative and operational lens, clarifying when automation contributes to equitable mobility and when it risks reinforcing inequality. RQ2 has thus been addressed by showing that travel time and generalised monetary cost can be jointly considered at the strategic planning stage through a proactive, dual-constraint measure, revealing inequalities that a purely time-based assessment would overlook.

Beyond these conceptual insights, the empirical findings provide practical lessons. Activity-specific time thresholds, such as the 10-minute limit applied to food POIs, substantially restricted positive integration outcomes. As a result, successful interventions were achieved in approximately two-thirds of the identified PIAs for food-related opportunities, indicating that complementary automated services can improve connectivity in theory but may not always be the most suitable solution for accessing highly time-sensitive services. Proximity and land-use structure therefore remain fundamental determinants of access.

With regard to CCAM integration modes, the results in Barcelona showed that, under the current access and egress time assumptions, single-sided integration was generally sufficient to restore affordable accessibility, while FMLM configurations were rarely required. This is mainly because, in the tested case, FMLM involves at least two transfers and requires paying the CS base fare twice, which increases TGTC. Different fare configurations could address the latter issue in other applications. Moreover, higher CCAM operating speeds were not consistently associated with better outcomes. Although 30 km/h reduced IVT, it sometimes increased the overall travel burden due to additional transfers or more complex itineraries. In contrast, lower speeds often yielded more efficient solutions by enabling simpler routes with fewer interchanges. These findings underscore that network coherence and transfer smoothness are as important as speed in shaping accessibility outcomes.

From an equity perspective, the vulnerability screening strengthens the legitimacy of targeted deployment by combining accessibility performance with structural socioeconomic disadvantage. In doing so, it avoids misclassifying affluent peripheral areas as PIAs and improves the identification of genuine transport poverty. Overall, equity indicators in Barcelona showed moderate but consistent improvements. Reductions in the CCI and FGT₂ indicated that accessibility gains were concentrated in neighbourhoods that previously experienced lower levels of access, confirming a pro-poor orientation. This approach addressed RQ3 by showing that zones for early deployment can be effectively prioritised through the proposed framework, which intersects low PT-based affordable accessibility with structural socioeconomic vulnerability, thereby distinguishing PIAs from zones that have low accessibility but are not necessarily socioeconomically disadvantaged.

Linked to the former, the limited change in the Palma ratio requires contextual interpretation. In Barcelona, the wealthiest decile included in the Palma calculation is largely concentrated in peripheral areas with relatively low PT accessibility, such as the neighbourhoods of Pedralbes and Sarrià-Sant Gervasi (e.g., Neighbourhoods 21, 23, and 24 in Fig. 5), yet without socioeconomic disadvantage. Because these areas were not prioritised for intervention, accessibility improvements were concentrated in lower-income neighbourhoods. In some cases, this resulted in a widening relative gap between the top and bottom deciles. From a horizontal equity perspective, which emphasises equal treatment and comparable improvements across groups, such an outcome may appear problematic. Likewise, from a purely utilitarian standpoint focused on maximising aggregate benefits, policy attention might instead favour raising overall accessibility averages rather than directing gains towards specific disadvantaged groups (Pereira et al., 2017). This divergence illustrates that equity outcomes are inherently sensitive to the normative framework adopted and to the choice of inequality metric.

In this sense, the framework adopted in this study does not follow a libertarian logic centred on user-pays principles and minimal redistribution, nor does it aim to maximise total system-wide gains irrespective of distribution. Instead, it aligns more closely with Rawlsian

egalitarianism (Rawls, 2001) and Capability Approaches (CAs) (Sen, 2005), particularly the difference principle, as well as with vertical equity concepts that justify unequal treatment when it benefits those who are worst off (Pereira et al., 2017). Under this perspective, raising disadvantaged areas above a minimum acceptable level of accessibility can be justified even if relative disparities across the overall distribution persist. The objective is therefore not to achieve uniform improvement across all groups, but to redistribute accessibility gains towards those with fewer initial opportunities. In this context, the proposed framework addresses RQ1 by showing that the integration of CCAM with PT can alleviate accessibility inequalities.

For the Barcelona case study, findings should be interpreted in light of the benchmark adopted for A_T and FGT_2 . The median PT-only affordable accessibility value serves as both the accessibility target and the FGT_2 poverty line and should be understood as a pragmatic relative benchmark rather than an absolute sufficientarian standard. In principle, a sufficientarian threshold should define the minimum level of accessibility required for people to meet essential needs with dignity. Such a threshold would ideally be defined through local policy standards, participatory processes, or empirical evidence linking accessibility to outcomes such as employment, health, or activity participation (Karner et al., 2025). However, no such agreed standard currently exists for Barcelona. For this reason, the median PT-only affordable accessibility value was used as a transparent, case-specific reference point, consistent with the pragmatic approach adopted by Karner et al. (2025) in their application of the FGT family of measures. The analysis therefore identifies zones that fall below the typical level of affordable accessibility in the study area, while explicitly acknowledging that this does not guarantee an absolute sufficient level of access. If a locally or universally defined minimum accessibility standard becomes available, it could be substituted for the median within the same framework.

In light of these findings, several policy implications emerge. First, spatial targeting is essential. Prioritising areas with both limited access and high vulnerability is more effective than a universal rollout. Broad deployment is not only financially challenging for operators, but it also fails to promote equity and may weaken the impact on underserved populations. Second, reducing interchange friction can generate accessibility gains comparable to or even surpassing those achieved by increasing vehicle speeds. Coordinated timetables and accessible transfer environments that reduce transfer time and perceived disutility can meaningfully lower overall travel burden. Finally, policy-oriented frameworks should account for users' willingness-to-pay to improve their accessibility while maintaining a strict affordability lens. Strategies such as the cost tolerance buffer provide a transparent governance instrument by making the trade-offs between system efficiency and individual affordability explicit. This approach allows for marginal cost increases only when they are accompanied by measurable gains in opportunity and improved average cost performance.

7. Conclusion

The integration of CCAM into the PT network, particularly in the form of CS, offers an opportunity to support a more integrated, accessible, and equitable mobility system. However, the benefits of this integration are not guaranteed. They depend on how these services are deployed and whether they address existing gaps in access, particularly for populations at risk of transport poverty. By accounting for both travel time and monetary cost, this study places affordable accessibility at the centre of the strategic planning process rather than treating it as an ex-post outcome.

To operationalise this idea, the study develops a framework comprising three main stages. First, areas with low baseline PT affordable accessibility are identified and combined with socioeconomic indicators such as income, employment rate, and access to private cars to define PIAs. Second, different integration strategies are evaluated, including FM, LM, and FMLM configurations, assuming different speeds

for CS, to identify all feasible integration options. Third, a two-phase optimisation approach is applied to determine the most suitable integration modes and paths. This approach first prioritises closing accessibility gaps and subsequently minimises the maximum TGTC, shifting the focus from aggregate system efficiency to a user-centric logic that protects individuals from excessive financial burdens.

Applied to Barcelona, the results showed that targeted PT-CS integration can lead to clear improvements in both accessibility and equity. On average, affordable accessibility increased by 18.1% across the city and POI groups. More importantly, by design, these gains are concentrated in disadvantaged areas. This is reflected in a 38.8% improvement in the CCI and a 57.6% reduction in transport poverty severity, measured by the FGT_2 index. Overall, this research has shown that strategically integrating CCAM with PT can help reduce accessibility inequalities (RQ1), provided that deployment follows equitable prioritisation principles (RQ3) and accounts not only for travel time but also for other travel-related costs (RQ2).

Notwithstanding these contributions, several methodological limitations should be noted. Fixed thresholds introduce clear cut-offs that may not fully capture behavioural flexibility, as travellers may accept slightly longer or more expensive trips under certain conditions. This issue has been partially addressed through the introduction of a cost buffer during optimisation but could be examined in more detail. While the CO measure was selected for clarity and policy interoperability, future research could explore continuous decay or gravity-based approaches that avoid reliance on discrete limits. Moreover, although the wage-based TGTC benchmark offers transparency, alternative definitions based on income distribution percentiles or expenditure-based transport burden indicators could provide further nuance.

Furthermore, the affordable accessibility assessment selects the fastest itinerary for each OD pair and evaluates its TGTC, rather than searching the full Pareto frontier of non-dominated paths across the time-cost plane (Conway & Stewart, 2019; Pereira et al., 2024). Although a robustness analysis showed that this simplification had no significant effect in the analysed case study, this targeted test does not constitute a complete multi-objective search and may omit other non-dominated combinations of waiting, walking, in-vehicle time and transfers. Direct optimisation over the complete TGTC formulation therefore remains an important direction for future methodological development.

As explained, the optimisation methodology proposed in this study is designed as a strategic accessibility-planning framework rather than a real-time operational deployment model. Its primary objective is to identify the maximum potential of integrating CCAM with PT to alleviate transport poverty in priority intervention areas by minimising travel times and users' total generalised travel costs. Consequently, certain operational realities are outside the scope of this strategic phase. Specifically, the framework does not currently incorporate real-world demand data, dynamic congestion feedback, vehicle scheduling or empty-vehicle repositioning. Furthermore, it does not mandate a specific operational deployment mode, nor does it calculate the fleet sizes or agency costs required to implement these services.

While these omissions mean that the model cannot be deployed immediately by an operator without further analysis, this strategic decoupling is intentional. It allows transport planners to establish an unconstrained, equity-focused benchmark that identifies exactly where interventions are needed and what performance thresholds, in terms of travel time and cost, a CCAM service must achieve to successfully bridge the accessibility gap.

However, a clear next step in this research is to close the gap between strategic planning and deployment by coupling this framework with an operational simulation layer. Future iterations will introduce fleet-sizing constraints, dispatching algorithms and operator cost structures to evaluate how closely a realistic, budget-constrained CCAM deployment can match the strategic accessibility targets identified in this work. Extending the framework to include the comparative integration of

other shared modes, such as bike-sharing systems, would further enhance its practical applicability as a comprehensive tool for multi-modal urban planning.

It is also important to note that actual user uptake is bound by complex behavioural factors. A time-effective and financially affordable service does not automatically guarantee modal shifts, particularly among vulnerable populations who often suffer from non-spatial barriers. Behavioural dimensions such as trust in automated driving systems, safety perceptions during shared trips, digital literacy, and age-related technology acceptance heavily dictate final adoption patterns (Greifenstein, 2024; Martínez-Díaz & Montes Carbó, 2024). Consequently, another direction for future research lies in expanding the proposed planning framework to integrate, for example, advanced discrete choice or technology acceptance models.

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CRediT authorship contribution statement

Peyman Hashemi Baragoori: Writing – original draft,

Appendix A. Equity-based optimisation of PT-CCAM integration

This appendix presents the complete mathematical formulation of the two-phase lexicographic optimisation model summarised in Fig. 2 and explained conceptually in Section 3. The notation and corresponding descriptions are provided in Table A1, followed by the ordered objective functions, constraints and Phase 1 reference values used in Phase 2. The formulation is presented in general terms, while the case-specific parameter values used in the Barcelona application are reported in Section 4.

The optimisation model is solved independently for each origin zone i and each POI group. From a given origin i , multiple candidate paths are defined to each potential destination zone j , representing different PT-CCAM integration scenarios (FM, LM, and FMLM) and CCAM operating speeds. For each OD pair, the model selects at most one feasible path. The binary decision variable x_p indicates whether path p is selected.

Moreover, all candidate paths are pre-filtered to satisfy the predefined time threshold (i.e., $t_p \leq T$) and TGTC threshold (i.e., $g_p \leq G$). Consequently, explicit time or monetary-feasibility constraints are not required within the optimisation model. The objective function is formulated to minimise the maximum TGTC among the selected PT-CCAM integration paths, directly limiting the highest generalised travel cost that any individual user may experience.

Table A1

Summary of notation, units, and definitions for the affordable accessibility optimisation model.

Notation (unit)	Description
Objective function	
Z_1 (POI count)	Minimising accessibility shortfall.
Z_2 (€)	Minimising the maximum TGTC of the selected paths.
Z_3 (POI count)	Maximising the total number of accessible POIs.
Set and indices	
i	Index of origin zone.
J	Set of all potential destination zones (PT-inaccessible zones) $j \in J$ reachable from origin i within the specified time and TGTC thresholds and not already served by PT.
P	Set of all feasible paths $p \in P$ from origin i to all $j \in J$.
Parameters	
T (min)	Time threshold: maximum allowable travel time.
G (€)	TGTC threshold: maximum allowable TGTC.
g_p (€)	TGTC associated with path p .
A_i (POI count)	Baseline accessibility: current PT-only accessibility value of origin i .
A_T (POI count)	Target accessibility: a statistical benchmark (e.g. median, Q_3) used as a normative reference to define sufficient access.
A_{gi} (POI count)	Accessibility gap: Required increase in accessibility: $\max(0, A_T - A_i)$.
a_p (POI count)	Accessibility contribution of path p (number of newly accessible POIs through zone j).
A_g^{init} (POI count)	Initial accessibility gain resulting from the Phase 1 optimisation, computed as the total number of newly accessible POIs provided by the selected PT-CCAM paths.
ΔA_g (POI count)	Minimum required increase in accessibility relative to the Phase 1 solution in Phase 2.
I_p^j	Binary parameter: 1 if the destination of path p is j ; 0 otherwise.
W_p^{init} (€)	POI-weighted average TGTC resulting from the Phase 1 optimisation.
ΔW (€)	Minimum required reduction in POI-weighted average TGTC in Phase 2 relative to the Phase 1 solution.
C_{max}^{init} (€)	Maximum TGTC among selected paths from the Phase 1 optimisation.
b	User cost tolerance buffer, expressed as a proportion of C_{max}^{init} .
Variables	

(continued on next page)

Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Margarita Martínez-Díaz:** Writing – review & editing, Validation, Supervision, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Table A1 (continued)

Notation (unit)	Description
x_p	Binary decision: 1 if path p is selected; 0 otherwise.
s (POI count)	Shortfall (slack): Continuous variable representing missing POIs if the target is unreachable.
C_{max} (€)	Maximum TGTC among the selected paths.

Phase 1 – Step 1

In the first step of Phase 1, the model minimises the accessibility shortfall variable s (as defined by objective Z_1 in Eq. (A1)), prioritising the closure of the accessibility gap for the origin zone. Once the minimum achievable shortfall s^* is determined, the second step fixes this value and minimises the maximum TGTC among the selected paths (as defined by objective Z_2 in Eq. (A5)). This two-step structure ensures that accessibility improvement is treated as the primary objective, while the maximum user cost is optimised only after the best attainable accessibility outcome has been secured. All paths with TGTC exceeding the threshold are excluded, ensuring affordability.

$$\text{Minimise } Z_1 = s \quad (\text{A1})$$

s.t.

$$\sum_{p \in P} a_p x_p + s \geq A_{G_i} \quad (\text{A2})$$

$$\sum_{p \in P} x_p^j \leq 1 \quad \forall j \in J \quad (\text{A3})$$

$$x_p \in \{0, 1\} \quad \forall p \in P, s \geq 0 \quad (\text{A4})$$

The accessibility constraint (Eq. (A2)) requires that the total accessibility gain delivered by the selected paths, $\sum_{p \in P} a_p x_p$, together with the slack variable s , is at least equal to the required accessibility gap A_{G_i} . The constraint in Eq. (A3) restricts the solution to selecting at most one path to a given destination zone for each origin, while binary and non-negativity conditions are imposed on the decision variables (Eq. (A4)).

Phase 1 – Step 2

Let s^* denote the optimal accessibility shortfall obtained after this first round. Once s^* is fixed, the second step focuses on affordability (Eq. (A5)).

$$\text{Minimise } Z_2 = C_{max} \quad (\text{A5})$$

subject to constraints in Eqs. (A2)-(A4) and additional constraints (Eqs. (A6)-(A8)):

$$s = s^* \quad (\text{A6})$$

$$C_{max} \geq g_p x_p \quad \forall p \in P \quad (\text{A7})$$

$$C_{max} \geq 0 \quad (\text{A8})$$

Phase 1 reference values

The Phase 1 optimisation provides reference values that are used in Phase 2. The total number of newly accessible POIs in Phase 1 (A_g^{init}) is (Eq. (A9)):

$$A_g^{\text{init}} = \sum_{p \in P} a_p x_p^{(1)} \quad (\text{A9})$$

Where $x_p^{(1)}$ denotes the value of the binary decision variable for path p obtained from the Phase 1 optimisation. Moreover, the POI-weighted average TGTC reflects the average cost of accessible opportunities (Eq. (A10)):

$$W^{\text{init}} = \frac{\sum_{p \in P} a_p g_p x_p^{(1)}}{\sum_{p \in P} a_p x_p^{(1)}} \quad (\text{A10})$$

The maximum TGTC faced by any user in the Phase 1 optimisation solution is (Eq. (A11)):

$$C_{max}^{\text{init}} = \max \left\{ g_p \mid x_p^{(1)} = 1 \right\} \quad (\text{A11})$$

From the Phase 1 solution, the indicators W^{init} and C_{max}^{init} are retained and used as reference parameters in the Phase 2 optimisation.

Phase 2

In Phase 2, the model evaluates whether users would be willing to accept a limited increase in C_{max}^{init} in exchange for improved accessibility outcomes. This is operationalised through a cost tolerance buffer b , which proportionally relaxes the initial maximum cost such that no selected path may exceed $(1 + b)C_{max}^{\text{init}}$. In this stage, the model maximises the total number of accessible POIs through objective Z_3 (Eq. (A12)), while maintaining affordability constraints.

Importantly, the accessibility target must be fully satisfied, and path uniqueness remains enforced. To justify the allowed increase in maximum cost, the new solution must deliver strictly more accessible POIs than the baseline solution and simultaneously reduce the POI-weighted average TGTC, i.e., W^{init} . In this way, any tolerated increase in the highest individual cost is justified by both higher opportunity access and a more favourable overall cost distribution across accessible destinations.

$$\text{Maximise } Z_3 = \sum_{p \in P} a_p x_p \quad (\text{A12})$$

Subject to the constraints expressed in Eqs. (A2)-(A4), (A6)-(A8), and the following additional constraints (Eqs. (A13)-(A15)):

$$C_{\max} \leq (1 + b) C_{\max}^{\text{init}} \quad (\text{A13})$$

$$\sum_{p \in P} a_p x_p \geq A_g^{\text{init}} + \Delta A_g \quad (\text{A14})$$

$$\sum_{p \in P} a_p g_p x_p \leq (W^{\text{init}} - \Delta W) \sum_{p \in P} a_p x_p \quad (\text{A15})$$

The optimisation model is formulated in general terms and can be applied using context-specific accessibility targets, travel time and TGTC thresholds, user cost tolerance buffers, minimum accessibility gains and required reductions in POI-weighted average TGTC. The case-specific routing assumptions, TGTC parameters and accessibility thresholds adopted for the Barcelona application are reported in Section 4, while the PT-CS path-generation and optimisation implementation settings are presented in Section 5.3. The model produces the final set of selected PT-CCAM paths for each origin zone and POI group, which is subsequently used to assess post-integration affordable accessibility and equity outcomes.

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