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Emerging transport modes and mobility hubs: a review of their impacts on CO_2 emissions

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The escalating demand for urban mobility has significantly contributed to increased CO_2 emissions, necessitating a shift towards sustainable, low-carbon transportation solutions. Emerging modes and concepts such as micro-mobility, shared mobility, electric mobility and mobility hubs offer promising pathways to reduce vehicle CO_2 emissions. This review explores the role of these modes in emission reduction, with particular attention to the integrative function of mobility hubs. This review synthesized current knowledge on the role of emerging transport modes in reducing urban CO_2 emissions. Our analysis through the Life-Cycle Assessment framework and Dynamic Mitigation Model demonstrates that while these modes can lower emissions by facilitating a shift away from private cars, their success is not a guaranteed outcome. Instead, their environmental benefit depends on managing the balance between modal substitution, operational logistics, and vehicle life-cycles. Mobility hubs are a pivotal strategy for mitigating the life cycle emissions associated with shared transport modes by enhancing integration and minimizing indirect emissions. Therefore, the review argues that advancing shared mobility from a niche option to a mainstream solution, supported by strategically implemented mobility hubs, is essential for achieving significant climate benefits. Prioritizing the coordinated deployment of emerging modes and hubs can capture their synergistic advantages, minimizing life-cycle CO_2 emissions and advancing the transition toward sustainable urban transport.

KEYWORDS
CO_2 reduction, emerging transport modes, micromobility, mobility hubs, modal shift to emerging modes, shared (electric) mobility

1 Introduction

The rising demand for mobility has driven a substantial increase in emissions (Intergovernmental Panel on Climate Change (IPCC), 2022), with the transportation sector being a major contributor (ITF, 2024). Private cars dominate urban mobility, producing high CO_2 emissions (Tian et al., 2022; González et al., 2019), air pollution (Adams and Requia, 2017; Degraeuwe et al., 2017), congestion (Struyf et al., 2022; Fan and Harper, 2022), and urban fragmentation (Delclos-Alio et al., 2023). In the EU, transport CO_2 emissions increased from 32 to 45% of total CO_2 emissions between 1990 and 2015, with road transport contributing 92% of these emissions (González et al., 2019). Cars alone accounted for half of road transport emissions, highlighting their significant role in rising CO_2 levels (González et al., 2019). This highlights the urgent need for practical strategies to decarbonize urban transport.

Over the past 15 years, mobility has undergone profound transformation, including the rise of shared mobility services, vehicle electrification, stricter environmental policies, advancements in automation, and disruptions caused by economic and health crises (de Bortoli, 2021). Evaluating these changes requires monitoring transport demand, modal shifts, and their impacts on energy and emissions. Van Wee et al. (2005) provided an early but still highly relevant framework for sustainable urban mobility, identifying six key determinants: (1) reducing transport volume in terms of number of trips or tonnes, (2) decreasing travel distances, (3) improving occupancy rates, (4) employing fuel-efficient and cleaner technologies, (5) changing driving habits to lower speed and a smoother driving style, and (6) shifting to sustainable modes like walking, cycling, and public transport. Notably, their framework predates the emergence of shared mobility, it does not explicity address these modes, which has since become a central element in sustainable transport strategies. Shared vehicles address several of these determinants by reducing trip volumes and distances, while shared electric vehicles additionally contribute through cleaner technologies. Together, they represent a new type of modal shift—away from private car use toward shared alternatives—thus advancing low-carbon mobility (Kuss and Nicholas, 2022; Svennevik et al., 2021; Bösehans et al., 2021).

Despite their promise, shared mobility systems are not without limitations. While they reduce direct in-vehicle emissions, indirect impacts such as shorter vehicle life cycles, rebalancing operations, and maintenance can offset these gains. Therefore, a life cycle perspective is necessary to fully assess the impact. In addition, significant uncertainties remain regarding emerging forms of shared and micro-mobility. Shared e-mobility systems are still at an early stage of development in most regions, and academic research on micromobility is likewise only beginning to take shape (Liao and Correia, 2022). The literature on shared e-scooters remains limited (Badia and Jenelius, 2021), and although shared micromobility services are expanding rapidly, there is still little evidence about their effects on travel behavior (Reck et al., 2022). As these modes are nascent, their technical performance is evolving quickly (ITF, 2024), which contributes to unstable findings. More broadly, the effectiveness and environmental impacts of such novel mobility types have not yet been comprehensively evaluated in either research or policymaking (D'Almeida et al., 2021).

In response, mobility hubs have emerged as an important strategy to centralize shared services, reduce rebalancing needs and vandalism, and encourage sustainable travel behaviors (Aydin et al., 2022). They are increasingly promoted in local and national policies (Department for Business, Energy and Strategy, 2022; Arnold et al., 2023), with investments in Europe, North America, and Asia (Nottingham City Council, 2020; Berndsen and Basta, 2021; Aono, 2019). However, their long-term environmental effectiveness remains insufficiently studied, and consensus on their definition and optimal design is still lacking (Rongen et al., 2022; Bernardes Real et al., 2021).

This review aims to synthesize existing knowledge on emerging modes including micro-mobility (bicycles and scooters), shared mobility, electric mobility, and their combinations into a comprehensive framework for evaluating their impact on modal shift and CO_2 reduction. It also explores the role of mobility hubs in reducing life cycle emissions, without engaging in hub typology debates. The analysis covers three key modes: conventional and electric carsharing, bikesharing, and scooter-sharing, chosen for their diverse environmental benefits and relevance to contemporary urban planning.

Previous studies have largely examined these elements individually. For instance, research has focused on the emission reduction potential of shared mobility (Kuss and Nicholas, 2022), of micromobility (Svennevik et al., 2021; Bösehans et al., 2021), or of the electrification of vehicles in reducing tailpipe emissions (González et al., 2019). Mobility hubs have similarly been studied across several functional dimensions, specifically regarding their role in service integration and accessibility (Berndsen and Basta, 2021), and more recently for improving operational efficiency in shared mobility (Aydin et al., 2022). Together, these studies indicate that the literature remains fragmented, with three notable gaps: first, a lack of a comprehensive synthesis linking micro-, shared, and electric mobility to decarbonization targets; second, limited attention to the environmental role of mobility hubs, particularly in regarding Life Cycle Assessment of emissions; and third, finding which suggest that shared mobility is currently relegated to a niche rather than a mainstream transport mode. These gaps also reflect limitations in the extant research, which frequently adapts narrow spatial scopes or short-term evaluations while overlooking systemic synergies and longitudinal behavioral dynamics.

This paper addresses these gaps through three contributions. First, it systematically synthesizes evidence on emerging transport modes with explicit reference to their CO_2 reduction potential. Second, it advances understanding of mobility hubs by positioning them not only as integration tools but also as strategies to reduce life cycle emissions. Third, it situates shared mobility within the broader trajectory from niche adoption to mainstream urban transport, highlighting the planning and policy conditions necessary for achieving meaningful climate benefits. Together, these contributions provide new insights for policymakers, planners, and researchers seeking integrated approaches to sustainable, low-carbon mobility.

The paper first outlines emissions determinants and environmental effects. It presents the methodology for assessing emerging modes and mobility hubs, followed by an analysis of shared and electric vehicles, the concept of mobility hubs, and factors influencing their effectiveness in reducing CO_2 emissions. The paper concludes with findings, implications for policy and practice, and recommendations for future research.

2 Methodology

We outline the approach for investigating emissions' determinants and environmental effects in transportation, as well as the methodology employed to explore the roles of modal shift and mobility hubs in reducing CO_2 emissions.

This section outlines the analytical framework for investigating the determinants of transport emissions and the environmental consequences of the transition toward emerging mobility systems. We introduce the Life-Cycle Assessment Model as an analytical framework and a dynamic Mitigation Model, as a novel theoretical perspective to explore the roles of modal shift and mobility hubs in reducing CO_2 emissions.

2.1 Life Cycle Assessment–based analytical framework

This study adopts a Life Cycle Assessment (LCA)–based analytical framework to synthesize how emerging transport modes influence both direct and indirect CO_2 emissions. Rather than proposing a new model, the framework integrates established emission determinants, modal shift dynamics, and life-cycle processes into a coherent conceptual structure suitable for comparative literature review.

Traditional LCA studies of transport emissions often assess vehicle technologies or transport modes in isolation, focusing on specific life-cycle stages such as vehicle production or use-phase emissions. However, the literature increasingly shows that the environmental outcomes of emerging mobility modes depend on interactions between modal shift, operational logistics, and life-cycle characteristics. In particular, technological efficiency gains may be offset by rebound effects, increased transport demand, or shortened vehicle lifespans. Figure 1 visualizes these interactions by linking classical transport emission determinants (van Wee et al., 2005) to modal shift outcomes and their corresponding direct and indirect emission pathways.

2.2 Direct and indirect emissions

In line with sustainability policies and research, we distinguish between direct and indirect emissions.

For mobility systems, direct emissions are further subdivided into vehicle use (tailpipe emissions from vehicle use, or "tank-to-wheel") and direct operational requirements. This latter category includes the emissions generated by rebalancing operations—the repositioning of shared fleets by service vehicles—which are a direct consequence of providing a flexible mobility service.

Indirect emissions, by contrast, arise from upstream fuel or electricity production ("well-to-tank") and broader life-cycle stages. In the European Covenant of Mayors for Climate and Energy (2019), these align with Scope 1 emissions (direct emissions occurring within the city boundary, including rebalancing) and Scope 2 emissions (indirect emissions from imported energy), respectively. As emphasized by Prussi et al. (2020), accounting for electricity generation and fuel production is essential to capture the full environmental footprint of transport systems.

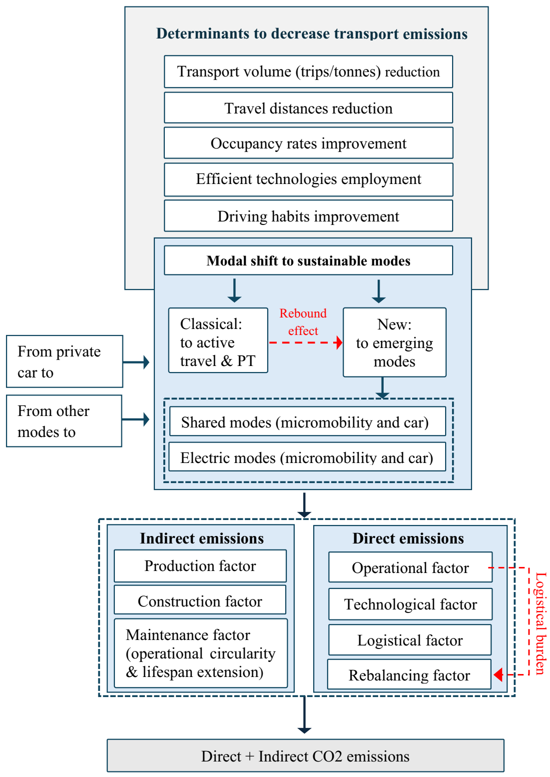

FIGURE 1
Life-cycle pathways linking transport emission determinants, modal shift, and direct and indirect CO_2 emissions.

Direct emissions have technical, logistical, and operational dimensions. They also encompass secondary operations required to support primary activities, such as the rebalancing of shared vehicles.

Technical factors influencing environmental impact include vehicle weight, shape, engine type, fuel type, and loading capacity (van Wee et al., 2005). Heavier vehicles consume more energy for acceleration, while electric engines are more efficient and emit fewer pollutants than internal combustion engines (ICE). Efficiency and emissions in ICE vehicles depend on fuel type (diesel vs. petrol), engine design, and exhaust after-treatment systems (van Wee et al., 2005).

Logistical factors relate to vehicle occupancy rates and load factors, reflecting how effectively a vehicle's capacity is used (van Wee et al., 2005). Additionally, infrastructure density, population distribution, and functional mix influence travel distances and energy consumption.

Operational factors are tied to vehicle usage and infrastructure characteristics, such as average speed, driving dynamics, and fluctuations between cruising and braking, all impacting energy consumption and emissions (van Wee et al., 2005). Anticipatory driving can significantly reduce fuel use and emissions, whereas aggressive driving increase emissions by 30–40% compared to defensive driving (Szumska and Jurecki, 2020). Despite shared mobility's sustainable image, it still has environmental impacts from operations like bike rebalancing and manufacturing (Luo et al., 2019).

Rebalancing or repositioning of shared vehicles is required in station-less business concepts. This is especially the case for shared scooters and bikes from high capacity to under-stocked locations. Such repositioning can substantially increase energy demand and– in the case of repositioning by fossil-fuel vehicles- also CO_2 emissions (Bonilla-Alicea et al., 2020). In London, 2.2 km of car travel was needed per 1 km of bike travel (Schuijbroek et al., 2017). Such rebalancing is typically carried out with trucks or vans, generating additional emissions (Pal and Zhang, 2017); in fact, it accounted for about 766,000 km of extra vehicle travel annually, offsetting much of the car trip reduction benefit (Fishman et al., 2014). Station-less systems have higher emissions, with rebalancing contributing to 36% of station-based and up to 73% of station-less system emissions (Luo et al., 2019).

Rebalancing significantly affects the use of CO_2 emissions. The frequency of rebalancing correlates with the fleet size and impacts maintenance-related emissions (Luo et al., 2019) and depends on the type of sharing involved, like station-based back-to-one or other service concepts. While reducing fleet size can increase emissions due to bike oversupply and frequent rebalancing, optimizing rebalancing strategies can mitigate these emissions (Luo et al., 2019). In station-based back-to-one shared services hardly any rebalancing is required, contrary to free-floating concepts.

Indirect factors include energy consumption and emissions related to other lifecycle processes of vehicles and infrastructure, such as production, construction, maintenance, and end-of-life processes like recycling. These stages play a significant role in determining the environmental footprint of transport systems (Van Wee et al., 2005). For instance, resource extraction, raw material processing, and manufacturing contribute heavily to emissions (Prussi et al., 2020). Maintenance processes, including component replacements and material use, further add to lifecycle impacts (Luo et al., 2019). Emissions from maintenance are crucial for evaluating the life cycle impact of shared vehicles particularly for shared micro-mobility. Recognizing these factors is crucial for accurately comparing modes of transport and understanding their environmental effects (Van Wee et al., 2005; de Bortoli and Christoforou, 2020).

A study by Chen et al. (2020) found that during production and maintenance, each bike is transported 1.67 km in China. Assuming 25% of bikes are dispatched daily, this results in 0.087 kg CO_2 emissions. However, the majority of carbon emissions from shared bikes originate from production, particularly from material production and processing, rather than from transportation or daily operations. The total emissions for a shared bike are estimated at 34.56 kg CO_2, with production accounting for 91%, operation and maintenance 4%, and disposal 5%. Raw material emissions contribute to 84% of production energy consumption, emphasizing the importance of managing energy usage during production to improve environmental sustainability (Chen et al., 2020).

Vandalism, through deliberate damage to transport modes, shortens their lifespan and necessitates frequent replacements, significantly impacting carbon emissions in mode-sharing systems (Luo et al., 2019). Repairing or replacing vandalized bikes consumes additional resources and energy, undermining carbon reduction efforts (Luo et al., 2019). Both bicycles and sharing infrastructure are designed for a ten-year lifespan, but effective maintenance can extend this to 15 years (Luo et al., 2019).

The environmental performance of shared micro-mobility is heavily influenced by the underlying operational business model, typically categorized into station-based (docked) and free-floating (station-less) systems. While Free-floating (station-less) systems offer greater user flexibility, they are more vulnerable to vandalism and physical degradation compared to their station-based modes (O'Kane, 2018). This increased critical concerns regarding vehicle longevity and the necessity for accelerated replacement cycles.

This scenario often compel operators to expand fleet sizes to compensate for high demand, wear and tear, or rebalancing inefficiencies. Crucially, these factors do not increase the emissions of the bicycles themselves, but rather escalate the Direct Operational Emissions stemming from the motorized service vehicles used for redistribution, alongside the broader life-cycle environmental impacts of manufacturing (Luo et al., 2019). Similar challenges are emerging for free-floating car-sharing models; however, there is currently a paucity of literature specifically quantifying the impact of reduced vehicle lifespans on the net carbon balance of station-less shared automobile systems.

To minimize rebalancing needs, reduce vandalism, and extend the lifespan of shared modes while lowering life cycle emissions, the literature highlights the role of mobility hubs as an effective mitigation strategy. By centralizing shared services, improving security, and optimizing operations, hubs can reduce indirect emissions and enhance the environmental performance of emerging mobility systems. Complementary measures, such as improved fleet management and more durable vehicle design, further support these outcomes.

2.3 Conceptual framework

This study applies an LCA–based analytical framework to examine how emerging mobility modes activate determinants 1, 2, 4, and 6 of the sustainable transport framework proposed by van Wee et al. (2005). Rather than treating these determinants as independent variables, the review adopts modal shift as its central analytical lens, reflecting evidence that shifts to emerging modes simultaneously affect occupancy, energy intensity, and life-cycle CO_2 emissions. This approach enables the identification of cascading effects that are often overlooked in determinant-by-determinant analyses.

Although emerging mobility modes and mobility hubs are increasingly discussed in the literature, empirical evidence on their combined net CO_2 impacts remains limited. To address this gap, the review synthesizes findings across studies to identify conditions under which emerging modes contribute to net decarbonization, as well as circumstances that generate rebound effects, such as substitution away from active travel or increased logistical emissions.

The Dynamic Mitigation framework (Figure 2) integrates these insights by linking the decarbonization potential of emerging modes to their realized environmental performance. While shared and electric mobility can reduce emissions through car substitution and first/last-mile integration, three recurring systemic risks are identified: negative modal substitution; substitution patterns between transport modes, life-cycle emissions related to production, maintenance, and vehicle lifespans, and operational and logistical emissions (including rebalancing). Mobility hubs are conceptualized as targeted interventions that mitigate these risks by consolidating operations, extending asset lifespans, and reducing indirect emissions, thereby supporting net urban decarbonization.

2.4 Selection and quality assessment

To ensure a comprehensive and systematic review, scientific papers and reports were collected using Google Scholar and Scopus, focusing on studies based on field experiments, surveys, GPS data, simulation models, and scenario analyses. Keyword searches covered micro-mobility, shared mobility, electric mobility, modal shift, CO_2 emissions, and mobility hubs (Table 1).

To ensure the scientific rigor of the review, the identified studies were evaluated based on their methodological contribution to CO_2 quantification. We conducted a multi-stage screening process: first reviewing titles, abstracts, introductions, conclusions, followed by thorough examination of full texts to assess suitability for data extraction. Reference lists were screened using backward snowballing to identify additional literature.

While the primary objective was to establish the link between modal shifts to shared and electric modes and the role of mobility hubs in mitigating emissions, we applied a formal quality assessment filter:

Phase 1 (Modal Shift): We first prioritized studies quantifying the shift from private cars or other vehicles to shared/electric modes. These were evaluated based on the transparency of their emission factors and the empirical basis of their data (e.g., utilizing GPS trackers or validated simulation models).

Phase 2 (Mobility Hubs): We subsequently examined mobility hubs as intermodal nodes designed to consolidate and optimize shared mobility services. Given the paucity of empirical literature explicitly quantifying the direct CO_2 impact of hubs, our analysis focuses on their capacity to mitigate operational inefficiencies identified in Phase 1—such as rebalancing-related externalities and premature vehicle depreciation. Furthermore, we explore how hubs may

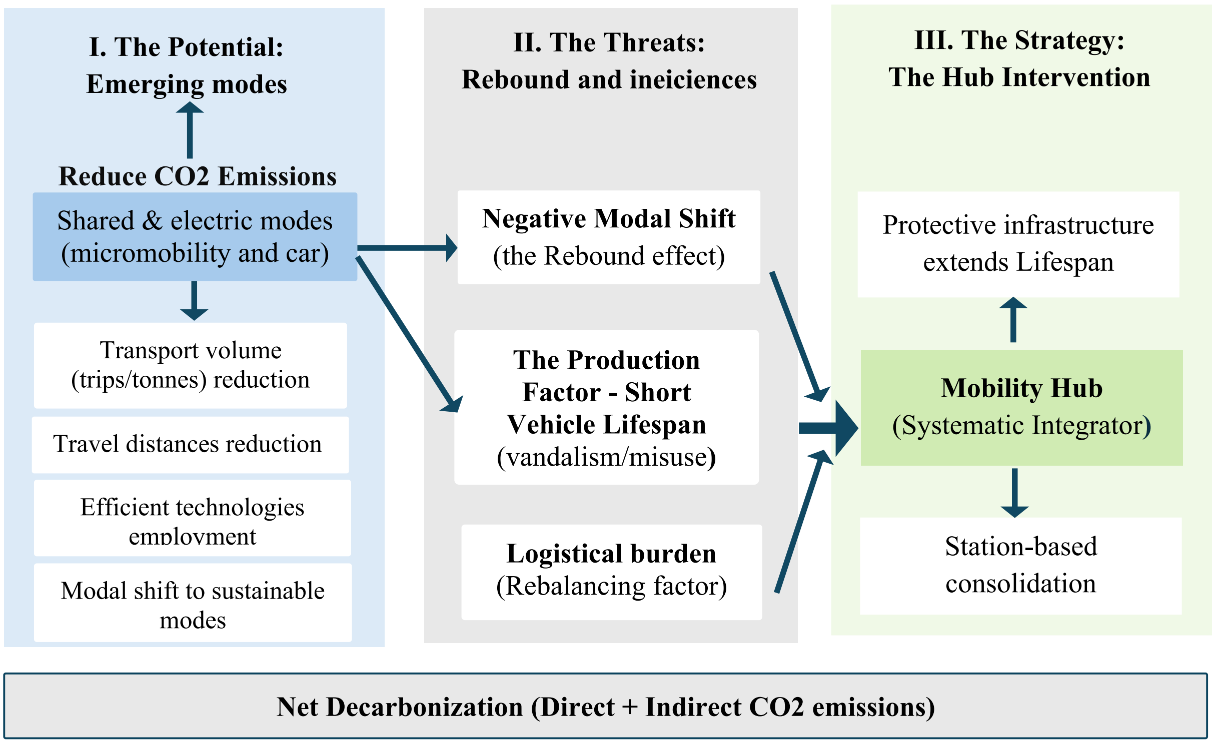

FIGURE 2
The dynamic mitigation model: mobility hubs as systemic integrators.

counteract potential rebound effects, such as induced demand resulting from freed-up road capacity as private vehicle usage declines.

We focused on studies published between 2016 and 2024 to capture the most recent technological advancements, with three exceptions (2011–2015) included for their foundational data. Ultimately, 118 studies were excluded due to redundancy or lack of quantitative CO_2 metrics, leaving a total of $N = 71$ publications for data extraction: 34 sources on the modal shift and 37 sources on mobility hubs (Figure 3). While the review primarily targets English-language literature, a high- relevance German research was included. The analysis focuses on European contexts, particularly Germany and Netherlands, while integrating comparative data from the US, UK, and China to assess generalizability.

To manage the methodological and contextual heterogeneity of the sources, we adopted a qualitative synthesis of consensus trends based on modal shift and mobility impact descriptions rather than comparing exact numerical values. This approach accounts for methodological and contextual heterogeneity, recognizing that findings from diverse locales (e.g., London vs. Beijing) are shaped by different factors, for instance varying transport habits. By organizing these studies in the Appendix by location and impact description, we provide a transparent basis for comparing findings across diverse landscapes while identifying the current lack of standardized CO_2 reporting as a significant research gap.

Studies were selected based on three criteria: (i) examining shifts from car and/or other modes to shared mobility, (ii) focusing on (shared) electric modes, and optionally (iii) quantifying the impact on CO_2 emissions. While we primarily address lifecycle CO_2 emissions (often referred to in literature as CO_2e), sources limited to use-phase emissions were included, with noted limitations to ensure a transparent assessment of the current state of the field. For simplicity, the term CO_2 is used throughout. Although comprehensive, the review acknowledges that the dynamic nature of this field makes complete coverage difficult.

The following sections present key findings, categorized by the LCA determinants, with a detailed overview provided in Table 2.

3 Mobility and CO_2 emission changes considering emerging modes

3.1 Types of emerging modes

Emerging modes refer to innovative and flexible mobility solutions that complement or substitute traditional private car use and conventional public transport. They are typically technology-based and prioritize sustainability, efficiency and accessibility. While this study primarily evaluates emerging transport modes (e.g., micromobility, shared, and electric mobility), it also examines mobility hubs as the critical multimodal infrastructure required to integrate and optimize these services.

Micro-mobility includes lightweight vehicles (under 500 kg) designed for relatively short distances (less than 15 km), powered by humans or electricity, and available for private ownership or sharing (Liao and Correia, 2022). Examples include bicycles, scooters, skateboards, segways, and hoverboards (Dia, 2019). These vehicles offer a cost-effective unimodal alternative to private cars for short trips (Smith and Schwieterman, 2018; Liao and Correia, 2022; Woods, 2019) or serve as first-mile and last-mile solutions for public transport (Liao and Correia, 2022). Micro-mobility improves access to public

TABLE 1 Sets of keywords for systematic literature review.

Theme	Content involved in keywords
Shared mobility	Emerging modes, innovative modes, shared micro-mobility; shared scooters, scooter-sharing, shared bike, bike-sharing, shared car, carsharing, sustainable modes, sustainable transport modes.
Electric mobility	Emerging modes, electric micro-mobility; e-scooters (sharing), e-bike (sharing), and e-car (sharing), sustainable modes, sustainable transport modes.
Modal shift to emerging modes	Shift from private car to shared modes, electric modes, shift from PT to, short distance, access egress modes, first/last mile, owned car, car ownership, conventional car, travel time, travel distance, travel cost
CO_2 emission	CO_2 emissions from vehicle use, from the production of fuels and electricity and of other lifecycle activities (production, maintenance and recycling of vehicles and infrastructure). Life cycle, life cycle emission, used emission, in vehicle use, direct emissions, indirect emissions.
Mobility hubs	Transport services, mobility hub, multimodal hub, e-mobility hub, station, access egress modes, first/last mile, seamless mobility.

transport nodes, increasing the overall attractiveness of public transportation (Gu et al., 2019; Abduljabbar et al., 2021).

These modes can reach areas poorly served by public transport or difficult for cars and active travel (Schwinger et al., 2022), potentially reducing car dependency and traffic congestion (Dia, 2019; Masoud et al., 2019). Smaller vehicles are more energy-efficient, using less energy than larger vehicles (Tillemann and Feasley, 2018). The popularity of micro-mobility is rising, offering a sustainable, flexible, cost-effective transportation option in some countries (Shaheen et al., 2020). In places like Netherlands, with a strong cycling culture, competition from existing modes is more pronounced. This study primarily focuses on shared and electric two-wheel vehicles within the micro-mobility framework.

Shared mobility provides short-term access to transport modes like (electric) cars and micro-mobility vehicles, such as scooters and bikes, based on demand (Shaheen et al., 2015). It aims to serve as an alternative to private cars for short trips and first/last-mile connections to public transport. Shared cars serve both short and longer multi-modal journeys (Shaheen et al., 2015). The goals of shared mobility include reducing private car ownership and usage, minimizing space for parking and movement, transitioning to post-fossil vehicles, and supporting public transport. Integrating these options with public transport enhances urban liveability and reduces congestion (Rongen et al., 2022). Key factors for improving carsharing include price, availability, access, and vehicle type, supporting the transition to post-fossil fuel vehicles.

Electric vehicles (EVs) are crucial for sustainable transportation due to their high energy efficiency (Usmani and Rösler, 2015). This category includes electric cars, e-bikes, and e-scooters, all of which provide climate-friendly options, especially for short trips in congested areas. EVs contribute to reduced pollution and noise in urban environments. However, lifecycle emissions can vary among electric modes based on battery type, materials, and production processes.

Mobility hubs are multimodal interchanges where discrete transport modes are co-located and digitally integrated. As intermodal nexuses, they synchronize shared mobility services with mass transit and active transport networks, serving as the foundational prerequisite for a cohesive multimodal ecosystem (Geurs et al., 2022; Miramontes et al., 2017).

Conceptually, this study frames hubs as "spatial anchors" that mitigate transfer penalties—the temporal and psychological friction associated with switching modes. By providing seamless connectivity and reducing "availability anxiety," hubs increase the propensity for modal shift from private vehicles to integrated transit chains (Aydin et al., 2022; Berndsen and Basta, 2021).

Beyond behavioral influence, hubs act as operational catalysts that enhance the commercial and environmental performance of emerging modes. By centralizing charging infrastructure and streamlining rebalancing logistics, hubs stabilize the stochastic usage patterns inherent in shared mobility (Aydin et al., 2022). Under this paradigm, the hub functions as a regulatory and digital gateway, transitioning fragmented "last-mile" tools into a synchronized, reliable extension of the mass transit backbone.

As illustrated in Figure 4, these emerging modes exhibit significant functional overlap and complementarity. This section evaluates their distinct characteristics and their collective impact on urban transport sustainability, specifically focusing on the modal shift from private vehicle ownership to integrated, shared alternatives. By physically and digitally anchoring these services, mobility hubs enable the following integrated travel configurations:

First/Last-Mile Synchronization: Shared (electric) micro-mobility acts as a high-frequency feeder to high-capacity transit trunks, effectively bridging the spatial gap between low-density residential areas and primary transport nodes.

Intermodal Substitution: Strategic placement of shared electric vehicles within hubs provides a competitive alternative to private car use for medium-to-long-range orbital or tangential trips—routes typically underserved by conventional fixed-route transit.

Despite these challenges, shared mobility typically reduces car use and travel distances when aligned with sustainable transport policies. The next section examines the transition from private cars to these emerging modes, highlighting steps towards a sustainable urban future.

3.2 Shift from private cars to shared vehicles (micro-mobilities and cars) in unimodal and or multimodal chains

Emerging modes enhance public transport accessibility and efficiency while reducing car usage and ownership (Burrieza, 2019). While some studies focus on mobility shifts, others assess impacts on CO_2 emissions. This distinction matters, as mobility shifts alone do

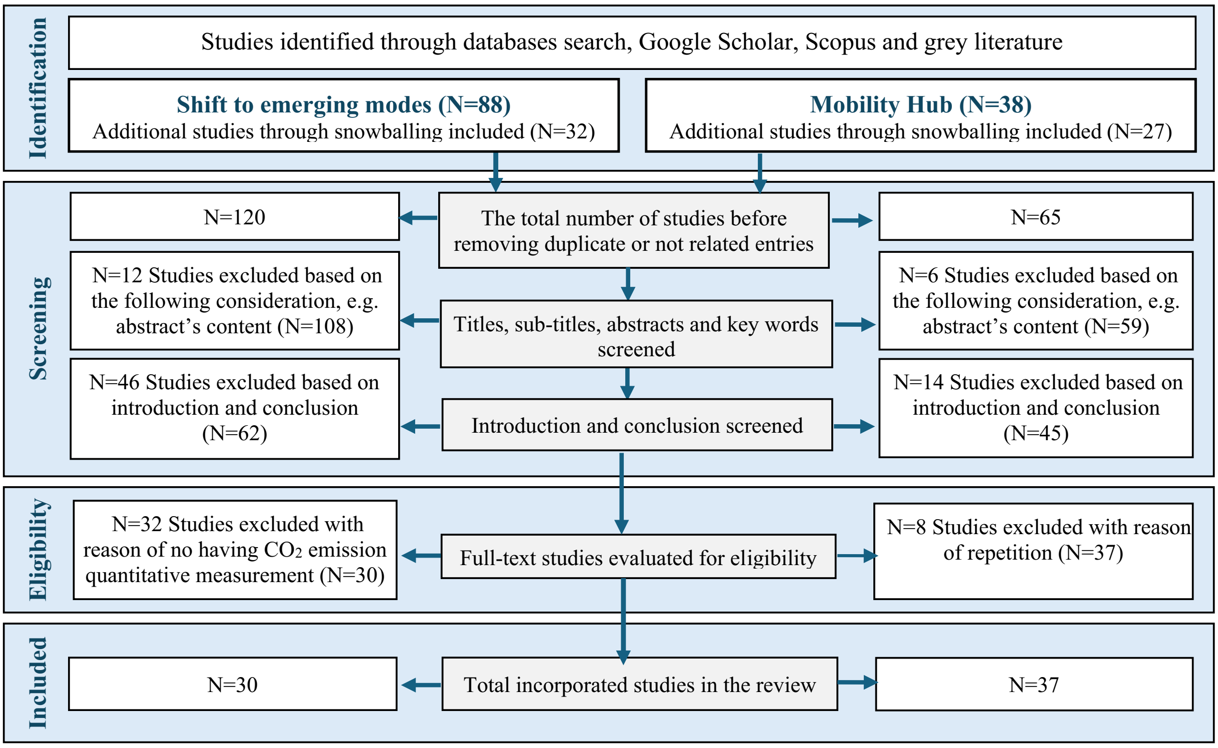

FIGURE 3
Flowchart of search and selection of literature for both areas: modal shift and mobility hubs in this study.

not guarantee environmental benefits, particularly when they increase travel demand or modal shifts from active modes to motorized transport.

Emerging modes can inadvertently increase CO_2 emissions through longer or more frequent trips. For instance, in Dublin, car-sharing raised car use by 60% among non-car owners, leading to higher travel costs and emissions (Rabbitt and Ghosh, 2013). Similar trends have been observed elsewhere, highlighting the potential risks associated with poorly managed shared mobility. This section explores the transition from conventional private cars to shared mobility, micro-mobility sharing and carsharing, highlighting steps towards sustainable urban transport. The reviewed literature spans global studies, but findings may not universally applicable, for example from Europe may not translate directly to China (Liao and Correia, 2022).

3.2.1 Micro-mobility sharing

This section reviews studies on shared micro-mobility, particularly shared bicycles and scooters. In the literature, these modes are often analyzed together, due to their similar roles in short-distance travel. However, discussions specifically on scooters remain limited.

Shared micro-mobility can operate independently or integrate with public transport. For instance, in London, it is partly combined with public buses (D'Almeida et al., 2021), while in Dublin, walking complements micro-mobility (Murphy and Usher, 2015). A Rotterdam study found shared micro-mobility, particularly shared bicycles and e-mopeds, effectively serve as egress options for metro trips (Montes et al., 2023). Integration with public transport improves the total travel experience by reducing overall travel time, especially in high-density areas where multimodal travel is common. The study also highlights that young travelers and frequent public transport users are more inclined to adopt shared micro-mobility, indicating that targeted collaborations between public transport and shared mobility providers can be beneficial. In Netherlands, bicycles dominate home-end trips, walking is preferred for short activity-end trips, and well-integrated micro-mobility complements public transport (Stam et al., 2021). However, some studies highlight competition with public transport particularly for short-distance trips. For example, Van Marsbergen et al. (2022) found that bicycle-sharing programs (BSPs) primarily support unimodal travel or travel with limited integration with urban transit. In the HTM-fiets bicycle program, only 9% of BSP trips were combined with transit. Similarly, Pfertner (2017) for Würzburg in Germany found that 46% of bike-sharing trips replace public transport rather than complement it, with the remainder replacing 27% walking, 18% private biking and only 9% introducing new mobility options. BSPs often replace other sustainable modes like public transport and walking, rather than private cars and barriers such as poorly located drop zones and high costs reduce their complementarity with transit. Nevertheless, envisaging only the use of vehicles, total mobility CO_2 emissions decline, as bicycles have zero emissions. These findings suggest that while bike-sharing can enhance public transport, it may also compete with it, particularly in cities with well-established transit networks.

Despite these challenges, bike-sharing systems contribute to multimodal transport, decreasing car use, traffic congestion, and CO_2 emissions, while also enhancing public health and urban liveability (Barbour et al., 2019; Ricci, 2015; Liao and Correia, 2022). The growth of bicycle-sharing systems is largely driven by their reduced environmental impact (Bonilla-Alicea et al., 2020), though other public-sector sustainability goals and private-sector commercial interests also play roles. Importantly, evidence shows that while bike sharing can lower CO_2 emissions compared to users' previous

TABLE 2 Overview of the modal shift literature review in this study.

References	Country	Changes in mobility (mainly modal shift)
Modal shift to shared mobility		
Modal shift to shared micro-mobility (bike and scooter)		
Abduljabbar et al. (2021)	General	Potential of micromobility to cut emissions and travel timesaving.
Liao and Correia (2022)	General	Private car to shared e-micromobility for short trips Decrease car ownership and car use Greater adoption when integrated with public transport hubs
INRIX (2019)	General	Private car to shared micromobility
Ma et al. (2020)	Delft	Shared bike increases use of train and decreases that of tram and bus
D'Almeida et al. (2021)	Edinburgh	Shift from different modes to shared bicycles
Pfertner (2017)	Würzburg, Germany	Shift from private bike, PT, walking and non-travelers to shared bike Decrease ownership of private car Reduce CKT
Montes et al. (2023)	Rotterdam, Netherlands	Shared micro-mobility as an egress for metro trips Complements PT, barriers include poor drop zones and high costs
Stam et al. (2021)	Netherlands	Bicycles dominate home-end trips Shared micro-mobility complements PT Younger travelers favor shared modes
Van Marsbergen et al. (2022)	Netherlands	Bike sharing programs replace sustainable modes, limited integration with transit, need for better planning and pricing
Modal shift to shared conventional car		
Jung and Koo (2018)	Urban areas, South Korea	Private car to shared car
Nijland et al. (2015)	Netherlands, In general	Shift from private car, PT, cycling to shared car
		Untraveled to shared car
		Decrease private car ownership
		Decrease Traveled distance
Schreier et al. (2018)	Bremen, Germany	Private car to shared car Reduce CKT
Pfertner (2017)	Würzburg, Germany	Shift from private bike, PT, walking and non-travelers to shared car Decrease ownership of private car
Martin and Shaheen (2016)	Calgary and Vancouver, Canada & Seattle, Washington, D.C., & San Diego, USA	Shift from private car, PT, cycling, and walking to shared car
		Decrease car ownership
		Reduce CMT
Rabbitt and Ghosh (2013)	Dublin, Ireland	Private car to shared car
Firnkorn and Müller (2011)	Ulm, Germany	Private car to (free-floating) carsharing Reduction of private car ownership
Giesel and Nobis (2016)	Berlin & Munich, Germany	Reduction in private car ownership by (free-floating) carsharing Increase car shedding rate Reduced planned car purchases
Van der Linden et al. (2025)	Netherlands	Private car to carsharing Decrease car ownership Reduce CO_2
Modal shift to electric modes		
Modal shift to electric bike		
McQueen et al. (2020)	Portland, USA	Private car to e-bike
Kruijf et al. (2018)	North Brabant, Netherlands	Shift from private car, conventional bike, and "other' to e-bike
Cairns et al. (2017)	Brighton, UK	Shift from private bike, PT, and walking to shared e-bike

(Continued)

TABLE 2 (Continued)

References	Country	Changes in mobility (mainly modal shift)
Hiselius and Svensson (2017)	Sweden, Urban areas & rural areas	Shift from private car, PT, and cycling to e-bike
Kämper et al. (2016)	München, Frankfurt/Main, Braunschweig/Hannover, & Bremen/Oldenburg	Shift from motorized transport, petrol car, conventional bike to e-bike Less CTM
Astegiano et al. (2019)	Germany	PT to e-bike (base scenario) Private car to e-bike (policy scenario)
Modal shift to shared electric micro-mobility (e.g., bike, scooter and cargo bike)		
Bourne et al. (2020)	Europe, North America, Australia, & New Zealand	From any mode to private or shared e-bike
Weschke et al. (2022)	Germany	Shift from private cars, walking, cycling, PT, and other shared modes to shared e-scooter
Reck et al. (2022)	Zurich, Switzerland	From almost all modes to shared e-scooter From almost all modes to shared e-bike
de Bortoli (2021)	Paris, France	Shift from private bike to shared bike E-Scooter to shared e-scooter E-moped to shared e-moped
Bonilla-Alicea et al. (2020)	General	Shared smart bike Smart dock bike
Campbell et al. (2016)	Beijing, China	From almost all modes to shared bicycle
		From almost all modes to share e-bicycle
Hollingsworth et al. (2019)	Raleigh, USA	Shift from private car, PT, cycling, and walking to shared e-scooter
		Decrease passenger miles traveled
Smith and Schwieterman (2018)	Chicago, USA	Private car to shared e-scooter
Krauss et al. (2022)	Berlin, Düsseldorf, Paris, Stockholm, Melbourne & Seattle	From all modes to e-bike (including private/shared cars and bicycles, public transport, taxis/ride-hailing, walking, and other micro-mobility). From all modes to e-scooter (similar broad mode shift).
Towards the shared electric car		
Baptista et al. (2014)	Lisbon, Portugal	Private car to e-carsharing
		Decrease car ownership, parking demand, & transport cost A complement to public transport
Martin and Shaheen (2016)	San Diego, USA	Shift from private car, PT, cycling, and walking to shared e-car
		Decrease car ownership
		Reduce CMT
Liao and Correia (2022)	General	Shift from private car and PT to shared e-car
Jung and Koo (2018)	Urban areas, South Korea	Private car to e-shared car Decrease car ownership Reduce CO_2

travel modes, its overall environmental benefits are strongly contingent on optimizing rebalancing operations and localizing bike production (D'Almeida et al., 2021). Conventional shared bikes typically cover 1–1.6 km per trip, with variations observed across different regions, including Europe, the US, and Asia (Boor, 2019; Shen et al., 2018; Campbell et al., 2016). In Washington D. C. bike sharing trips are generally under 3 miles (Bonilla-Alicea et al., 2020). Private bicycle trips tend to have longer distances. In Netherlands, private bike trips average shorter than 3–3.5 km (De Haas and Huang, 2022). Shared bikes can effectively substitute short car trips (Abduljabbar et al., 2021) and public transport trips, particularly in urban settings.

In Netherlands, the "OV fiets" scheme has significantly enhanced train usage by offering accessible last-mile options at transport hubs (Mbugua et al., 2025). According to Ma et al. (2020), the scheme led to a 17% increase in Delft, on the other hand, 60% of OV fiets users were reported to go less by bus and tram. Similarly, Mobike, a former competing shared bike system, contributed to a 14% increase in train use, while also their bus and tram usage declined substantially, namely by 40% (Ma et al., 2020). In parallel, both systems enhanced their role in reducing car use (34% or 37% respectively).

Pricing greatly influences shared micro-mobility adoption. Excessive costs for shared modes discourage their usage, while competitive pricing, especially for egress trips, can increase their

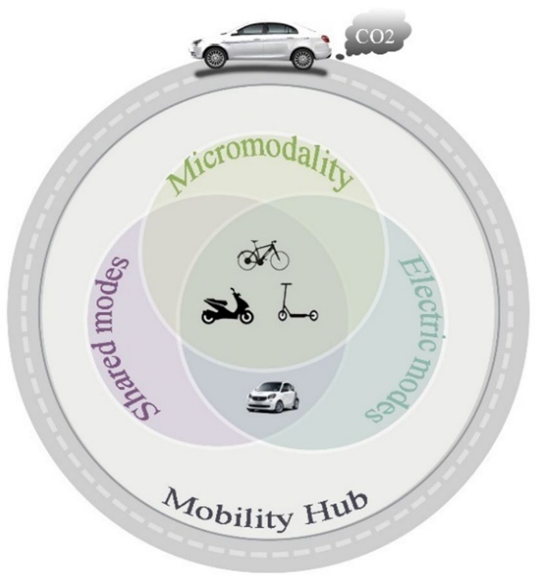

FIGURE 4
Potential innovative mobility options which can be offered in mobility hubs (created by author).

attractiveness (Montes et al., 2023). Additionally, familiarity with shared micro-mobility positively influences adoption rates. Encouraging first-time usage through promotional campaigns or trials at transit hubs could foster long-term use (Montes et al., 2023). Stam et al. (2021) highlight that younger travelers prefer shared mobility and tailored first/last mile infrastructure can boost sustainable transport adoption.

De Bortoli (2021) compared the environmental impact of private and shared bikes in Paris using Life Cycle Assessment (LCA), focusing on the effects of switching between modes rather than the extent of modal shift. Private conventional bikes, with a lifespan of 20,000 km, exhibit the lowest environmental impact per passenger-kilometer traveled (pkt), emitting just 10.5 g CO_2/pkt. By comparison, private e-bikes emit 320 kg CO_2 over their lifecycle, translating to 26 g CO_2/pkt for a lifespan of 12,500 km and reducing to 16 g CO_2 /pkt when extended to 20,000 km. Shared e-bikes, while convenient, emit 24% more CO_2 than shared mechanical bikes, with 70% of their emissions stemming from manufacturing.

Bonilla-Alicea et al. (2020) assessed the environmental impacts of bike-sharing versus conventional bicycles over 10 years in a hypothetical city, without accounting for a modal shift. They found that stationless shared bikes have a higher environmental footprint compared to the station-based system. The production of bikes emits 1,460 kg CO_2 per bike (148 Pts) over its estimated lifespan, while the infrastructure for stations contributes an additional 479 kg CO_2 per bike (55 Pts). Over the lifecycle, emissions amount to 0.13 kg CO_2/km for bikes and 0.069 kg CO_2/km for station infrastructure. To match the environmental benefits of station-based systems, station less bikes require a 71% vehicle substitution rate, whereas stations require only 38%. Both systems generate significant emissions from rebalancing, but stationless bikes need 1.8 times more ridership to offset their overall environmental impact.

INRIX (2019) reported that shared bikes and shared scooters could replace 50% of car trips in the US, 60% in Germany, and 70% in the UK for distances under 3 miles, helping reduce traffic congestion and emissions. As previously discussed, Pfertner (2017) emphasized the versatility of bike-sharing as both a complement to public transport and an alternative to car use. However, this example is an exception regarding the typical modal shift, as there is no shift from the private car, which contrasts with the patterns typically observed. A summary of all studies is provided in Appendix 1.

3.2.2 Sharing of conventional cars

According to Shaheen et al. (2019), carsharing reduces total (= private and shared) car-km and private car ownership, contributing to reductions in fuel consumption, and greenhouse gas emissions while offering alternative mobility options among car-free households. It also reduces reliance on public transport for primary trips but often enhances first and last-mile connections. The effects on bicycle usage vary based on local conditions and user preferences. Rabbitt and Ghosh (2013) found that in Ireland, carsharing positively impacts travel behaviors and helps reduce CO_2 emissions, especially in densely populated areas. Participants who sold their cars to join a carsharing system reduced their Car Kilometers Traveled (CKT) by 9%, which saved an average of 1,197 kg of CO_2 annually. Non-car owners who joined the system saved 337.2 kg of CO_2, while those who sold their cars saved about 859.8 kg. Overall, carsharing reduced Ireland's CO_2 emissions by 86 kt annually. If electric carsharing systems were adopted, the savings could increase to up to 895 kt. Active travelers and public transport users who sold their cars saved 145.7 kg and 316.6 kg of CO_2, respectively. However, non-car owners experienced a 60% increase in car dependence, with raised travel costs and CO_2 emissions.

Van der Linden et al. (2025) conducted a case study in Netherlands with 1,281 Greenwheel users. The study revealed that station-based car sharing replaces up to 11 private cars per shared vehicle. Around 41% of environmentally conscious users disposed of at least one private car after joining the service, indicating a meaningful shift in car ownership patterns. In contrast, skeptical users demonstrated smaller reductions, suggesting they retained some or all of their private cars. Before joining, many users owned more than one private car, making the observed reductions particularly relevant. Car sharing primarily substitutes private car trips (25%) and public transport trips (36%), indicating that it serves as both an alternative to car ownership and a flexible addition to existing transport options. Overall, users reported a net CO_2 reduction of 30%, highlighting the environmental benefits of car sharing in urban mobility system.

Nijland et al. (2015) analyzed carsharing's impact on annual CO_2 emissions in Netherlands in 2014. Prior to using shared cars, participants traveled 38% of kilometers by private car, 35% by train, 4% for by public transport and 2% by cycling. Carsharing led to an 18% reduction in annual travel (1,600 km), which resulted in an 11% decrease in CO_2 emissions (250 kg/year; percentage by authors). However, the shift from sustainable transport modes to carsharing added 160 kg of CO_2 (7%; percentages by authors), leading to a net reduction of 90 kg/year (4%). Carsharing also lowered average car ownership from 0.85 to 0.72 cars per household, reducing CO_2 emissions by an additional 85–175 kg annually due to lifecycle effects. In total, carsharing achieved a net CO_2 reduction of 175–265 kg per respondent per year, corresponding to an 8 to 12% reduction in emissions related to car use and ownership. Nijland et al. (2015) highlight that convenient carsharing services help promote the shift from private car ownership, encouraging users to adopt carsharing rather than purchasing new vehicles. A similar conclusion is drawn by Liao et al. (2020).

Chen and Kockelman (2016) found US carsharing users consumed 51% less energy and emitted less CO_2 from vehicle use compared to private car users. This reduction is primarily due to fewer overall trips and the shift from private to shared vehicles. Additionally, carsharing reduces the demand for parking infrastructure and fuel consumption. Similarly, Firnkorn and Müller (2011) evaluated the environmental impact of car2go in Ulm, Germany. They showed that car2go, a free-floating carsharing system, decreased the total number of cars and reduced the carbon footprint of carsharing users from 2,786 kg to between 146 and 312 kg annually, a reduction of 5 to 11%.

Jung and Koo (2018) studied the impact of carsharing on greenhouse gas emissions in Seoul. They found that while carsharing increases CO_2 emissions due to a shift from public transport to shared cars (an increase of 11,833 t CO_2 daily), it reduces emissions by shifting from private cars to shared vehicles (−5,929 t CO_2) and lowering other car lifecycle emissions (−3,093 t CO_2 daily). The result is a net daily increase of 2,809 t CO_2, or an annual rise of 1,026,000 t CO_2. Jong and Koo suggest that this represents approximately 1.2% of total road transport emissions. More reduction can be achieved if shared cars are electric ones.

Pfertner (2017) examined mobility behavior changes in Würzburg, Germany also of shared cars and bicycles. The study identified key factors contributing to CO_2 reduction, such as lower emissions per kilometer from smaller, modern vehicles and fewer overall car kilometers. A significant modal shift to carsharing was noted, with 50% of trips replacing public transport, 32% replacing private car trips, 29% replacing new mobility trips, 22% replacing private bicycles and walking, and 10% replacing rental cars. Overall, carsharing led to a net CO_2 reduction of 650 tons annually, consisting of 629 tons from reduced fossil car kilometers, 10 tons from shared cars being more efficient, and a 31-ton increase due to shifts from public transport and active travel. This net reduction represents about 1% of local transport emissions.

Giesel and Nobis (2016), in contrast, focused more on conceptual insights related to ownership behavior, showing that both station-based and free-floating carsharing in Berlin and München significantly reduce private car ownership. Among the 819 surveyed DriveNow users, 6.5% reported selling their cars, and 7.1% avoided planned purchases. Similarly, among the 227 surveyed Flinkster users, 15.3% reported selling cars, and 8.3% avoided planned purchases. In Bremen, Schreier et al. (2018) reported that each shared car replaced 16 private ones, removing about 5,000 vehicles from the streets, which also reduced parking demand. Users of shared cars also drove 50% fewer kilometers, utilizing shared cars for three-quarters of their trips.

Martin and Shaheen (2016) studied car sharing in five US and Canadian cities. They found that Car2go resulted in a 2–5% reduction in car ownership, with 7–10% of users forgoing vehicle purchases. The impact on PT varied by context, with changes in bus usage ranging from a 32% decrease to a 5% increase, reflecting shifts in how users employed carsharing for first/last-mile connections. Car2go led to a 6–16% decrease in car miles traveled (CMT) per household, translating to a 12% average reduction in GHG emissions, with each Car2go vehicle displacing 4 to 14 tons of GHG annually. Similarly, Jochem et al. (2020) found that among regular carsharing users in several European cities, between 3.6 and 16.1% reported selling a vehicle after joining the scheme, while 14.3 to 40.7% indicated that they had postponed or foregone a vehicle purchase. Consistent with these findings, Van Gerrevink (2021) reported that, in 2008, European carsharing users drove 2.5 times fewer kilometers than private car users. All the mentioned studies have been summarized in Appendix 2.

Shared cars emit less CO_2 than private cars over their lifecycle. While shared micro-mobility (e.g., scooters) has low use emissions, depending on the return model, repositioning and mishandling may increase total emissions. Shifting from public transport and cycling to carsharing can increase travel distances, despite lower private car emissions (Jung and Koo, 2018). Overall, private vehicles rank lowest in CO_2 performance, while shared vehicles vary based on the analysis focus.

3.3 Shift from private cars to (shared) electric vehicles (micro-mobility vehicles and cars) in unimodal and or multimodal chains

Shared electric mobility has similar mobility effects as shared fossil-fuel mobility but offers greater sustainability due to technological differences. It is discussed separately here to avoid confusion with studies that jointly analyze shared and electric vehicles. Shared electric mobility can contribute to reduced traffic congestion by offering alternatives to private car use—particularly single-occupancy trips—while also promoting environmental sustainability and enhancing accessibility (Liao and Correia, 2022). The following sections explore the CO_2 impacts of shifting from private cars to shared electric micro-mobility and vehicles.

3.3.1 Electric bicycle (sharing)

Electric bicycles (e-bikes) can significantly reduce CO_2 emissions from transportation (McQueen et al., 2020, referring to Portland). There is a willingness to cycle longer distances with e-bikes than with conventional in the US (McQueen et al., 2020) and Netherlands (Sun et al., 2020). They enable longer distances with less physical effort compared to conventional bikes, making them more effective at replacing private car trips (Bourne et al., 2020, many countries; Cairns et al., 2017, Brighton, UK; Kruijf et al., 2018, Netherlands). E-bikes potentially lead to less traffic congestion, lower energy consumption, and improved air quality (McQueen et al., 2020; Sun et al., 2020). E-bike sharing systems can enhance these benefits by increasing accessibility and mobility options, further promoting sustainable urban transport.

Studies show that a large percentage of short commutes in Sydney (67%) and Melbourne (76%) rely on private vehicles. In the US, half of all car trips are under 5 km, while in Europe, over half are less than 8 km. Shared e-bikes and e-scooters are emerging as low-carbon alternatives for these short trips (Woods, 2019), particularly those around 2 km, due to their greater convenience and ease of access compared to carsharing (Liao and Correia, 2022). At the trip level, e-bikes have been shown to outperform taxis and public transport for shorter distances in Zürich (Guidon et al., 2019), while e-scooters demonstrate similar advantages over public transport in San Diego (Arnell et al., 2020). However, while electric micro-mobility options are viable for short distances, they are less effective for longer trips (Smith and Schwieterman, 2018).

Reflecting on these findings, the potential for shared e-bikes and e-scooters as alternatives to private cars may vary by region. In Europe, where public transport systems are generally well-developed, the impact of shared micromobility may be more limited. In contrast, in the US and Australia, where public transport is often less accessible and travel distances are longer, shared e-bikes and e-scooters could play a crucial role in replacing short car trips. The tendency of Americans to use cars even for very short trips, sometimes within walking distance, highlights the considerable potential for shared micromobility to reduce car dependency in such contexts. It should be noted, however, that private electric bicycles may also offer substantial potential, as suggested by Hiselius and Svensson (2017), who found that private e-bikes could significantly reduce car use in Sweden.

E-bikes, e-scooters, and other micro-mobility options enhance accessibility to hard-to-reach areas (MacArthur et al., 2017; Smith and Schwieterman, 2018) and are more efficient due to their higher speeds. Astegiano et al. (2019) examined the shift from cars and public transport to traditional bikes and e-bikes for trips under 50 km from 2015 to 2050. They found that road pricing significantly reduced car use and CO_2 emissions, while a base scenario, which projected trends without additional policy interventions, led to greater declines in public transport use as natural growth favored e-bike adoption. The impact varied by country, with Netherlands showing less change due to its strong cycling culture, suggesting toll policies could drive more significant shifts (Astegiano et al., 2019). However, it is important to note that this study focused only on Scope 1 (tank-to-wheel) emissions, which may underestimate the total lifecycle emissions impact of mode shifts.

Kämper et al. (2016) studied the CO_2 impacts of e-bike use and ownership in 5 cities in Germany, and Hiselius and Svensson (2017) for urban and rural areas in Sweden. They found that e-bikes significantly reduce reliance on cars, sometimes competing with public transport. In Germany, 41% of e-bike trips replaced car trips and 38% replaced conventional bike trips (Kämper et al., 2016). In Sweden, where 80% of urban car trips are under 3–4 km (Naturvårdsverket, 2019), e-bikes effectively substituted car use in urban and rural areas (Hiselius and Svensson, 2017). In Germany, car was the most replaced mode for any travel motive. In Sweden, e-bike commuters mainly used cars before, while for e-bike leisure this was the conventional bike.

Kämper et al. (2016) found that e-bikes reduce CO_2 emissions by at least 25% per passenger kilometer (pkm) compared to other motorized transport, with a 90% reduction when switching from petrol cars, saving nearly 150 g CO_2 per pkm. However, switching from conventional bikes to e-bikes increases emissions by 7.4 g CO_2 per pkm. The shift from less sustainable modes to the e-bike was analyzed to save 2,400 kg of CO_2 weekly, while the shift from conventional bikes and walking to the e-bike would add 50 kg. Overall, e-bikes significantly lower emissions, especially for frequent car trips, potentially replacing up to 80 million pkm of car travel for trips under 15 kilometers in Germany.

Hiselius and Svensson (2017) examined the impact of private e-bikes on CO_2 emissions in rural and urban Sweden. E-bike users reduced car use by 55 km per week in urban areas and 62 km in rural areas. This resulted in weekly CO_2 reductions of 7.7 kg (urban) and 8.6 kg (rural), averaging 8.2 kg. This corresponds to a 14–20% reduction in annual emissions, depending on the frequency of e-bike use throughout the year. However, the study considers only direct (tank-to-wheel) emissions and does not account for lifecycle emissions, which may lead to an underestimation of the full environmental impact.

Regarding average trip distances, e-bike sharing has a median trip length of 2 km, e-scooters of 1.8 km per trip (Liao and Correia, 2022), while conventional shared bikes have average trip lengths of 1–1.6 km (Boor, 2019; Shen et al., 2018). In specific urban case studies, shared electric modes have been found to overlap with public transport and taxis (Guidon et al., 2019), pointing to replace short car trips (Abduljabbar et al., 2021). For instance, e-bikes often have the potential to replace car (45%) and traditional bike (32%) trips (Kämper et al., 2016). McQueen et al. (2020) studied e-bike adoption in Portland, USA, focusing on private e-bikes. They found that e-bikes mainly replace car trips (72%), followed by public transport (13%), conventional bike trips (12%), and walking (2%). Increasing e-bike market share from 0 to 15% could reduce daily car passenger miles traveled from 28.9 million to 25.5 million (12% reduction) and CO_2 emissions from 8,079 to 7,088 metric tons per day. Each e-bike would then save around 225 kg of CO_2 annually, even assuming the current carbon intensity of U.S. electricity. However, cars would still account for 98.9% of total emissions at a 15% e-bike mode share.

Campbell et al. (2016) explored shared bike and e-bike usage in Beijing. They found that 17% of shared e-bike users had previously used private cars, compared to 8% for shared bikes. Among shared e-bike users, 30% had been public transport users before, while 20% of shared bike users came from public transport. Regarding current bike users, 11% of shared e-bike users and 17% of shared bicycle users reported switching from private bicycles. Furthermore, 27% of shared e-bike users and 49% of shared bike users previously walked as their primary mode of transport. Mean distances of shared e-bike trips are 4.5 km, and those of shared e-bike trips are 2.9 km, making them suitable for longer distances and potentially replacing up to 80 million pkm of car trips. The study noted that conventional bike-sharing is influenced by habits and environmental factors, often competing with bus use. E-bike sharing is more effective in low-density areas and appeals primarily to younger males with lower education and income levels. Travelers previously accustomed to unsheltered modes such as walking, private cycling, and private e-cycling were found to be more likely to switch to shared (e-)bicycles than those who previously relied on sheltered modes like cars, buses, or metro. While e-bikes are efficient for longer trips, they can lead to congestion and safety concerns at intersections, but they have strong potential to promote sustainable urban mobility.

Reck et al. (2022) analyzed mode choices among 540 participants in Zurich to estimate former modes of current micro-mobility users. Among current shared e-bikes users, 9% of their travel distance previously involved walking, 43% public transport, 15% car, 29% bicycle, and 5% private e-bike trips. Shared e-bikes have gross emissions of 83 g CO_2/pkm, resulting in a net increase of 25 g CO_2/pkm compared to the emissions of replaced modes (58 g CO_2/pkm). In contrast, for private e-bike users, 9% of travel distance originated from walking, 29% from public transport, 48% from car, 14% from the bicycle, and 5% from another private e-bike usage. In contrast, private e-bikes achieved a net reduction of 54 g CO_2/pkm, with gross emissions of 34 g CO_2/pkm and replaced modes averaging 88 g CO_2/pkm. These results underscore the importance of Life Cycle Assessment (LCA) when evaluating micro-mobility impacts, demonstrating the greater CO_2 reduction potential of private e-bikes relative to shared services.

Krauss et al. (2022) analyzed the impact of shared electric scooters and bicycles in six cities worldwide. They found that shared e-bicycles trips in Berlin, Düsseldorf, Paris, Seattle and Melbourne formerly took place by walking (25–49% dependent on the city), public transport (13–39% of which metro 2–33%, buses 4–11%) or used taxi or ridehailing

(6–14%).[1] The study compares the CO_2 emissions per pkm.[2] Shared bicycles emit 0 g CO_2/pkm during use, while this is 0.1–10.9 for shared electric bicycles (dependent on the city and hence to the characteristics of national electricity production). In addition, there are 23–24 g CO_2/pkm for servicing (repositioning). The total life cycle emissions are higher:46.1–47.3 g CO_2/pkm for shared bicycles and 60–70.6 g CO_2/pkm for shared e-bicycles. These LCA emissions are less than for a fossil-fuel private cars, average (of all envisaged cities) than for electric private cars, also less than for taxi/ridehailing and bus/shuttles, however larger than for metro and urban rail. Taking account of changing pkms per mode the e-bicycle lets net emissions increase in Berlin and decrease in the other cities. The explanation for Berlin's deviation is the larger share of private bicycle use and public transport and the lower share of taxi use and ridehailing there, compared to the other cities analyzed. All the mentioned studies have been summarized in Appendix 3.

3.3.2 Electric scooter (sharing)

Multiple studies emphasize the potential of e-scooters as a transportation option. Hollingsworth et al. (2019) and PBOT (Portland Bureau of Transportation) (2019) found that shared e-scooters could replace 34% of car trips in the US, while Fitt and Curl (2019) reported up to 28% in New Zealand. Fearnley et al. (2020) found that 57% of shared e-scooter users integrate them with other modes, with notable shifts from walking (60%), public transport (23%), and cars (8%) to e-scooters in Oslo.

Reck et al. (2022) found that, on a distance basis, among current shared e-scooter users, 25% of their travel previously involved walking, 38% public transport, 15% car, and 13% bicycle trips. Shared e-scooters exhibited gross emissions of 106 g CO_2/pkm, resulting in a net increase of 51 g CO_2/pkm compared to replaced modes (55 g CO_2/pkm). Among current private e-scooter users, 19% of travel distance originated from walking, 27% from public transport, 25% from car, and 27% from bicycle use. Private e-scooters have gross emissions of 42 g CO_2/pkm, yielding a net reduction of 16 g CO_2/pkm relative to replaced modes (58 g CO_2/pkm). As with e-bikes, the private versions of e-scooters in Zurich show lower emissions than the modes they replace, while shared versions show higher emissions.

Hollingsworth et al. (2019) analyzed the lifecycle emissions of station-less e-scooter sharing in Raleigh, US. Their survey found that 34% of e-scooter users would have driven a car, 11% would have taken a bus, 7% a bike, and 41% would have walked. Shared e-scooters emit 202 g CO_2 per passenger mile, compared to 414 g for private car use. Emissions are primarily from materials and manufacturing (50%) and repositioning (43%). With an estimated lifetime mileage of 7,300 miles, shared e-scooters have higher emissions than buses (82 g CO_2/pass-mile) and private e-bikes (40 g CO_2/pass-mile). Urban density affects emissions, with denser areas reducing repositioning distances. Increasing repositioning distance to 2.5 miles raises emissions by 27%, and shortening the scooter lifespan to 0.5 years increases CO_2 emissions to 450 g. Strategies like enhancing urban density and extending e-scooter lifespan to 2 years could reduce emissions by up to 50%, achieving a net reduction of 141 g CO_2 per passenger mile.

Smith and Schwieterman (2018) examined shared e-scooters in Chicago, finding them effective for short trips (0.5–2 miles), increasing the share of non-auto trips from 47 to 75% in the city's North area and from 55 to 66.8% in the South and West areas. However, for longer trips (over 3 miles), e-scooters were less economical and mainly used for reaching bus or train stations. The study does not address carbon emissions changes related to the mode shift.

Weschke et al. (2022) found that shared e-scooters serve as feeder modes to improve public transport accessibility in Germany. They replace walking (42%), public transport (20%), biking (11.5%), and cars (11.3%) in Germany. However, with a gross lifecycle emission of 106 g CO2/pkm, higher than the emissions of the replaced modes, which range from 43 to 65 g CO_2/pkm, shared e-scooters result in a net increase of emissions. To reduce overall emissions, efforts should focus on reducing e-scooter emissions and promoting their use as a car alternative, improving parking, access, and flexibility to enhance adoption.

De Bortoli (2021) conducted an environmental assessment of shared second-generation e-scooters, focusing on lifecycle emissions rather than market shares or modal replacements. The study estimated an average lifespan of 7,300 km for shared e-scooters. For these vehicles, vehicle production accounted for 79% of lifecycle CO_2 emissions, followed by servicing (9%), infrastructure (10%), and electricity consumption (2%).

Optimized routing, servicing, and using electric vans were shown to reduce emissions by up to 9%, while electricity use remained minimal. The carbon footprint ranking for Paris showed that private mid-range and entry-level e-scooters emit less CO_2 per passenger-kilometer than shared e-scooters, while all e-scooter types emitted less than diesel buses, private motorcycles, cars, and taxis, but more than most other alternatives. Sensitivity analyses indicated that simply extending the lifespan would not be sufficient to make shared e-scooters less emitting than e-public transport in Paris. Overall, shared bikes and e-mopeds were found to consistently outperform shared e-scooters environmentally. Additionally, De Bortoli also noted that in U.S. conditions, shared micromobility modes globally rank between active modes and motorized modes in terms of global warming potential. Public transport presents a higher carbon footprint than in Paris due to a higher carbon intensity of electricity and a lower vehicle occupancy rate; furthermore, the carbon footprint from the infrastructure is also higher in the US (de Bortoli, 2021).

Krauss et al. (2022) found that shared e-scooter trips most commonly replace walking, ranging from 40% in Paris to 64% in Seattle. Subway trips are replaced in 1% (Seattle) to 30% (Paris) of shared e-scooter trips, taxi/ride-hailing in 4% (Berlin) to 12% (Melbourne), and buses in 5% (Düsseldorf/Paris) to 15% (Stockholm). Replacements of private fossil-fuel car trips by shared e-scooters are modest (1 to 7%), while electric car trips and private cycling are rarely replaced (up to 0.7 and 1 to 4%, respectively). The study shows that emissions of shared e-scooters, although on a different level, have a similar relation between use, servicing (repositioning) and total LCA emissions as shared e-bicycles: servicing and scope 3 emissions weigh heavy. Shared electric scooters have use-phase emissions of 2.8 g CO_2/pkm[3]

1 The remainder deriving from two slightly unlogic clusters (1: private trucks, private or shared cars, private or shared mopeds, private motorcycles; 2: shared or private e-scooters, private or shared bicycles, private e-bicycles) and a third cluster (would not have made this trip without, otherwise).

2 It also shows the net emission changes in tons, but the provided information does not allow to derive percentual magnitudes.

3 Unweighted average of Berlin, Düsseldorf, Paris, Stockholm Seattle and Melbourne (calculated by authors).

which is lower than most motorized mode alternatives, while total life cycle emissions amount to 97.5 g CO_2/pkm. Krauss et al. conclude that shared e-scooters reduce CO_2 emissions compared to the emissions of the modes which would be used otherwise in all six cities, in the non-European ones (Seattle and Melbourne). Overall, shared scooters have higher CO_2 emissions due to production and maintenance from shorter life cycles compared to privately owned vehicles. While shared electric scooters can reduce CO_2 when replacing high-emission vehicles, their total impact depends on their entire life cycle. All the mentioned studies have been summarized in Appendix 4.

3.3.3 Towards the electric shared car

Baptista et al. (2014) examine carsharing in Lisbon, Portugal, reporting reduced car ownership, parking demand, and vehicle costs. It further finds that within the carsharing fleet, shifting from conventional shared cars to hybrid and electric vehicles (EVs) can reduce energy consumption by 35 and 47%, respectively, along with CO_2 emissions by approximately 35 and 65%. These results reflect vehicle technology improvement, not account for modal shifts; therefore, the total city-wide emissions would be lower.

Martin and Shaheen (2016) examined the effects of conventional and electric car sharing on vehicle ownership, car miles traveled (CMT), and CO_2 emissions in five U.S. cities. They found that electric car sharing reduced total CMT, while conventional car sharing increased it. In San Diego, conventional car sharing had a more significant CMT reduction than electric, with each shared EV replacing fewer cars (1–7) compared to conventional (2–11). This led to a CMT change of −7% in San Diego versus −6% to −16% elsewhere. Overall, car sharing removed about 28,000 cars, with 25% of electric car users shifting from public transport, 11% from private cars, and 34% from walking. CO_2 reductions were 6% per car-sharing household in San Diego, while conventional systems saw reductions of 4 to 18% in other cities, though specific data for electric car-sharing were lacking.

Liao and Correia (2022) found that electric carsharing generates lower emissions per passenger-kilometer than conventional carsharing, partly due to the limited range of battery electric vehicles. While carsharing reduces driving distances and public transport use, it increases walking and encourages more active, sustainable modes. However, the average trip distance for electric carsharing is relatively short (2.7–3 km), indicating that e-bike sharing may be a more suitable alternative for these trips. The study did not provide specific CO_2 reduction percentages.

Jung and Koo (2018) showed that shifting from private to shared electric vehicles—particularly for delivery and one-way trips—can significantly increase usage and reduce emissions. Replacing 50% of gasoline stations with EV charging stations and vehicles can reduce CO_2 emissions by 64% annually, using the Dutch energy mix. Expanding charging infrastructure to 71.1% of gasoline/diesel stations can result in zero emissions from the modal shift. However, the net CO_2 impact also depends on the modes being replaced, as shifts from both private cars and public transit to car sharing may not fully offset emissions if they delay car ownership decisions. All the mentioned studies have been summarized in Appendix 5.

In summary, shifting from private cars to shared electric cars and micro-mobility options offers the potential for CO_2 reduction. However, achieving meaningful environmental benefits depends on effectively managing life cycle emissions and integrating these modes within sustainable urban mobility systems.

4 Mobility hubs concept, definition and characteristics

In recent years, the mobility hub concept has gained growing prominence in international transport planning as an emerging component of passenger transport systems (Geurs et al., 2022). Mobility hubs provide a sustainable alternative to car travel by integrating various shared mobility options in specific locations (Klanke, 2022). By combining shared services, mobility hubs promote shifts to emerging transportation modes (Aono, 2019) and play a crucial role in urban planning and transport policies (Weustenenk and Mingardo, 2023). Since their inception in Bremen in the late 1990s and the establishment of physical hubs in the early 2000s, mobility hubs have gained global popularity as a sustainable transportation solution (Arnold et al., 2023). While initially focused on emissions reduction, mobility hubsnow contribute more broadly to local and national policies (Department for Business, Energy and Strategy, 2022; Weustenenk and Mingardo, 2023).

Recent empirical evidence further underlines the value of integrating shared mobility with public transport. For example, a societal cost–benefit analysis of the Dutch public transport bike system (OV-fiets) demonstrates that bike-sharing integrated with public transport can generate significant societal benefits, including improved first- and last-mile connectivity, increased public transport use, and positive environmental and welfare effects (Mbugua et al., 2025). Such findings reinforce the role of mobility hubs as key enablers of multimodal travel, enhancing public transport performance (Transport for Greater Manchester, 2019) while improving social accessibility (Nottingham City Council, 2020). Core objectives of mobility hubs therefore include equitable access to activities, stimulation of local economic activity, congestion reduction, and the promotion of shared mobility services (CoMoUK, 2019; Plymouth City Council, 2020).

Mobility hubs encompass a wide spectrum of types and scales, ranging from large, high-capacity hubs at major public transport nodes to small-scale, locally embedded facilities (Xanthopoulos et al., 2024). On the one hand, station-area mobility hubs—such as those developed around major railway stations—primarily function as regional or metropolitan interchange points, emphasizing high-quality integration between public transport and shared mobility services, including bike-sharing and car-sharing. These hubs typically serve longer-distance and multimodal trips and play a strategic role in network-level accessibility (Torabi kachousangi et al., 2022).

On the other hand, neighborhood mobility hubs are smaller in scale and more closely embedded within residential areas, focusing on short-distance trips, daily activities, and local accessibility (Rongen et al., 2022). These hubs typically offer shared mobility modes that can be used for unimodal trips or function as first-mile solutions connecting users to higher-order public transport stations (Rongen et al., 2022). By doing so, neighborhood hubs provide flexible transport options for residents without access to a private car, supporting car-light lifestyles while facilitating access to medium- and long-distance travel (Rongen et al., 2022). Together, these different hub types illustrate that mobility hubs are not a one-size-fits-all concept but a flexible approach that can be tailored to spatial context, travel demand, and policy objectives.

Despite their growing importance, the concept of a mobility hub remains ambiguous, with nouniversally accepted definition (Blad et al., 2022; Rongen et al., 2022). Various terms and definitions exist in the literature (Aono, 2019; Claasen, 2019; CoMoUK, 2019; Miramontes et al., 2017; Van Rooij, 2020), reflecting differences in scale, function, and policy context. As an increasing attractive topic, mobility hubs have become central to numerous theses, academic publications, and planning practices, as shown in Table 3.

Typically, mobility hubs are defined as recognizable physical locations that offer a variety of amenities and provide a range of shared transport modes while being integrated into public transport networks, thus facilitating multimodal mobility (Aono, 2019; Claasen, 2019; CoMoUK, 2019; Miramontes et al., 2017; Van Rooij, 2020; Blad et al., 2022; Anderson et al., 2017; Bell, 2019; Bösehans et al., 2021; Coenegrachts et al., 2021; Frank et al., 2021; Vianen, 2022; Rongen et al., 2022). Common keywords in these definitions include *strategic locations*, *sustainable multiple transport modes, shared modes, shared mobility services, seamless mobility, mobility services, economic services, node, and place*.

4.1 Role of mobility hubs to reduce CO_2 emissions

Mobility hubs play a critical role in enhancing the effectiveness of shared and emerging transport modes as sustainable alternatives to private car use. Beyond their functional purpose, hubs have the potential to reshape societal attitudes towards shared mobility (Karlsson et al., 2017). In some cultures, private car ownership continues to serve as a symbol of social status, while shared modes are perceived as low-status alternatives (Pojani et al., 2018; Chun et al., 2019). Empirical evidence from Germany suggests that hubs raise awareness and normalize shared mobility as a mainstream alternative (Miramontes et al., 2017). In this sense, mobility hubs act not only as infrastructural interventions but also as cultural and behavioral catalysts.

Functioning as centralized and accessible nodes, mobility hubs facilitate multimodal integration and strengthen the convenience of sustainable travel (Aono, 2019). Rather than directly enforcing behavioral change, they reduce barriers to adopting alternatives by improving connectivity and minimizing dependence on private cars (e.g., Liao and Correia, 2022; Alarcos Andreu, 2017; Miramontes et al., 2017; Pfertner, 2017; Claasen, 2019; Knippenberg, 2019; Van Rooij, 2020). Studies highlight that hubs increase public transport usage, improve first- and last-mile connections, and alleviate parking pressures by consolidating shared vehicles in accessible locations (Blad et al., 2022; Jorritsma et al., 2021; Kim, 2021). Pfertner (2017) reports that 83% of users considered mobility hubs sufficient to eliminate the need for private car ownership, offering convenient access to multiple transport options. Evidence further proofed that mobility hubs facilitate a shift away from private car ownership (Karbaumer, 2018; Liao and Correia, 2022; Storme et al., 2021), while Liao and Correia (2022) found that many users sold or postponed the purchase of cars after adopting hub-based services. These outcomes illustrate the capacity of hubs to enable modal shifts at scale.

From an environmental perspective, mobility hubs address several structural barriers that diminish the carbon-reduction potential of shared mobility. Although emerging modes can reduce emissions when substituting car travel, their benefits are often offset when they replace more sustainable modes, such as walking, cycling, or public transport (Hollingsworth et al., 2019; de Bortoli and Christoforou, 2020; D'Almeida et al., 2021; Reck et al., 2022; Weschke et al., 2022). Campbell et al. (2016), for example, illustrates that bike sharing in Beijing often substitutes bus trips in dense urban districts, while e-bike sharing complements public transport in suburban areas. These findings underscore the importance of context-sensitive hub design in maximizing carbon-reduction outcomes. Moreover, shared micromobility services face challenges such as short vehicle lifespans due to vandalism and misuse, which elevate life-cycle emissions per passenger-kilometer. By offering secure parking, charging facilities, and improved oversight, hubs extend vehicle lifespans, reduce production-related emissions, and mitigate these indirect environmental costs (Luo et al., 2019; O'Kane, 2018).

Another critical dimension lies in reducing the inefficiencies associated with vehicle rebalancing. The frequent repositioning of shared bikes, scooters, or cars to meet fluctuating demand is often carried out with fossil-fuel vans, which can outweigh the operational emission savings of shared fleets. Strategically designed hubs can significantly reduce the need for rebalancing by consolidating vehicles in high-demand areas, while also supporting complementary strategies such as incentivized user returns, bundled fleet operations, and electrified repositioning logistics (de Bortoli, 2021). Collectively, these measures reduce the energy intensity of fleet management and strengthen the environmental case for shared mobility.

Overall, mobility hubs represent a multifaceted solution to urban transport and climate challenges. By integrating diverse transport services, reducing inefficiencies, and improving both user experience and social acceptance, hubs strengthen the carbon-reduction potential of shared mobility. When strategically placed and supported by enabling policy frameworks, hubs can extend beyond niche interventions to become a mainstream contributor to sustainable, low-carbon urban transport systems.

5 Discussion and conclusions

This review synthesizes current knowledge on the role of emerging transport modes—including micromobility, shared mobility, and electric mobility—in reducing urban CO_2 emissions. Using a Life Cycle Assessment (LCA)–based analytical perspective, complemented by the Dynamic Mitigation framework, the analysis shows that while these modes can contribute to decarbonization by displacing private car use, their environmental benefits are not inherent or guaranteed. Instead, net CO_2 outcomes depend on how modal substitution patterns, operational logistics, and vehicle life-cycle characteristics interact within specific urban contexts.

5.1 Discussion

The transition of shared and electric mobility from niche applications to mainstream urban transport solutions is a non-linear and conditional process. The reviewed studies demonstrate that emerging mobility modes possess substantial potential to reduce private car dependency, but their realized environmental effectiveness is contingent on managing systemic trade-offs across the transport system rather than on technological improvements alone.

5.1.1 Trade-offs and rebound effects in the CO_2 performance of emerging mobility

A robust finding across the literature is that CO_2 reduction benefits are frequently undermined by unproductive modal substitution.

TABLE 3 Examples of mobility hub definitions since 2020.

Examples of definitions used in master thesis	
Li (2020)	A mobility hub is a physical place that integrates mobility functions and other facilities that benefit the neighborhood. By providing a variety of sustainable travel options and living facilities, the mobility hub facilitates residents' travel and daily life
Blad et al. (2022)	The mobility hub is a place where multiple sustainable transport modes come together at one place, providing seamless connection between modes, additionally offering shared mobility, including other features, ranging from retail, workplaces to parcel pick-up points
Van Gerrevink (2021)	A mobility hub is defined as a place where several (shared) modalities are combined. This could range from a station area including access/egress facilities to a small-scale hub with a few shared vehicles offered.
Vianen (2022)	A mobility hub is a recognizable place which offers a range of transport modes (e.g., carsharing, bike-sharing, bus etc.), but also other services (e.g., postal lockers, neighborhood library, kiosk etc.). There are different hub sizes, varying from larger hubs like train stations which combine a lot of shared services and transport modes, to neighborhood hubs which serve needs of people on a local level.
Examples of definitions used in academic publications	
Coenegrachts et al. (2021)	A location where shared mobility is concentrated. The shared mobility hub clusters different new and conventional mobility services at a physical location. Its functions, services, facilities, and infrastructure requirements depend on the local urban context, including the policy goals of the different stakeholders.
Examples of definitions used in the planning practice	
Alliance for Logistics Innovation through Collaboration in Europe (ALICE) (2020)	A physical location that enables the transfer to the most optimal modality for the onward journey.
Arup (2020)	In the current transport system, mobility hubs are commonly seen as physical places that connect a variety of transport modes. A mobility hub can be anything from a bus stop and a bike sharing station to an inner-city main train station.
Witte et al. (2021)	A physical link between transport modes that – in addition to its mobility function – can also serve as focal point for spatial development.
Metropolitan Transportation Commission (2021)	Serving as a community anchor, a mobility hub is a welcoming environment that enables travelers of all backgrounds to access multiple transportation options and supportive amenities. Built on the backbone of frequent and high-capacity transit, mobility hubs offer a safe, comfortable, convenient, and accessible space to seamlessly transfer across different travel modes.
Advier (2021)	At a transport hub on neighborhood level different sustainable and shared transport modes are linked with each other. Preferably, a mobility hub includes carsharing. Mobility hubs provide an easily accessible, visible and recognizable offer for end users. For policy makers, hubs represent a tool to enhance a shift towards sustainable transport and more efficient use of public space. Mobility hubs have primary elements like shared modes, bicycle parking, proximity to public/collective transport, easy access, branding, and secondary elements like storage facilities or meeting points for neighborhood activities.
Reisviahub.nl (2021)	A hub is more than a transport node where people can transfer between modes. The emphasis is on experience: living climate, recognisability, information, time saving, positive surprise and integration with the environment. It is the ideal place to link several facilities together. Think of facilities for travelers only, such as a kiosk, water tap, Wi-Fi, or transfer point for the hub taxi. But also think of general facilities such as a health center, a community school, or a shop. In short, a place where everything comes together.
Geurs et al. (2022)	A mobility hub is a physical location where different shared transport options are offered at permanent, dedicated and well-visible and where public or collective transport is available at walking distance.

Shared micromobility services often replace walking, cycling, or public transport trips rather than private car travel. When such substitution patterns dominate, net emissions may increase despite low or zero tailpipe emissions. In addition, multiple life-cycle studies document that operational rebound effects—most notably those associated with fleet rebalancing, maintenance, and premature vehicle replacement—can offset or even negate anticipated emission savings.

Empirical evidence indicates that shifts from private cars to shared cars or private electric bicycles yield the most consistent CO_2 reductions. In contrast, shared micromobility systems frequently exhibit higher life-cycle emissions per passenger-kilometer, an outcome largely attributable not to vehicle propulsion technology but to indirect emissions arising from logistics and shortened vehicle lifespans. These findings demonstrate that decarbonization outcomes depend more on system configuration and usage patterns than on vehicle technology alone.

5.1.2 Mobility hubs as systematic integrator of life-cycle emissions

The reviewed literature suggests that mobility hubs *may address* structural factors constraining shared mobility performance, primarily through mechanisms inferred from station-based systems and centralized fleet operations. However, it is important to distinguish between empirically demonstrated effects and mechanisms inferred from related evidence.

Life-cycle studies consistently show that vehicle production accounts for a dominant share of emissions in shared micromobility systems, often exceeding 70–90% of total life-cycle CO_2 emissions. As a result, vehicle lifespan emerges as a decisive determinant of environmental performance. While direct empirical studies isolating the CO_2 impact of mobility hubs remain limited, evidence from station-based and centrally managed systems suggests that secure and organized docking environments are associated with lower vandalism rates and longer service lifetimes. These findings support the inference that mobility hubs may contribute indirectly to emission reductions by extending vehicle lifespans and amortizing production-related emissions over greater travel output.

Similarly, multiple studies document that rebalancing operations—particularly when conducted with fossil-fuel service vehicles—represent a substantial source of indirect emissions. Centralized fleet organization and reduced redistribution distances, which are characteristic of hub-based or station-based systems, are consistently associated with lower logistical emissions. While these effects are well documented for station-based systems, their direct attribution to mobility hubs as integrated infrastructures remains an area where empirical evidence is still emerging.

5.1.3 Conceptual implications: mobility hubs as conditional system-level enablers

Beyond operational efficiencies, the review suggests that mobility hubs may function as system-level enablers within broader urban transport transitions. By improving visibility, intermodal accessibility, and spatial integration, hubs have the potential to reduce practical barriers to combining shared mobility with public transport and to support behavioral shifts away from private car ownership. However, evidence for such behavioral effects is largely indirect and context-dependent, drawing primarily on studies of intermodal integration rather than on evaluations of mobility hubs per se.

Accordingly, mobility hubs should not be interpreted as inherently decarbonizing interventions. Rather, their potential contribution to CO_2 reduction appears conditional on their ability to (i) increase substitution away from private car use, (ii) reduce indirect operational emissions, and (iii) support longer vehicle lifespans within shared mobility systems.

5.1.4 Methodological barriers and the standardization gap

A central limitation identified across the reviewed literature is the persistent lack of standardized CO_2 accounting. Differences in system boundaries, functional units, and treatment of indirect emissions significantly constrain cross-study comparability. Moreover, geographical heterogeneity, particularly in electricity generation mixes, introduces substantial variation in the carbon performance of electric and shared mobility systems. Identical interventions may therefore yield divergent outcomes across cities and regions.

These limitations underscore the need for future research to move beyond generalized performance claims. Context-sensitive threshold analyses are required to identify the specific car-replacement rates and operational conditions necessary to offset life-cycle emissions under local energy and mobility contexts. Such analyses would enable policymakers and planners to shift from uniform deployment strategies toward locally optimized mobility hub implementations.

5.2 Recommendations for research and policymaking

To advance shared mobility from niche to mainstream, we propose the following recommendations:

Focus on Replacing Car Trips: Cities should place mobility hubs in areas where they are most likely to replace car use (such as the edges of the city). If hubs are only located near existing train stations, they might simply replace walking or cycling instead of removing cars from the road.

Standardized Emission Data: To fix the lack of clear data found in this review, city authorities should require shared mobility companies to report their total CO_2 impact. This must include not just the trips themselves, but also the emissions from maintenance vans and the vehicles used to move bikes and scooters around.

Incentives for Hub-to-Hub Trips: Policies should encourage users and companies to move vehicles between hubs. This strategy minimizes the logistical burden associated with fleet redistribution—specifically the secondary emissions from service vans. By reducing the intensity of motorized rebalancing, hubs help prevent operational offsets, where the carbon costs of managing the shared system threaten to negate the environmental benefits gained from the modal shift.

5.3 Conclusion

This review demonstrates that emerging transport modes can contribute to urban CO_2 reduction, but only under clearly defined conditions. Their environmental performance is shaped by modal substitution patterns, operational logistics, vehicle lifespans, and local energy systems. Mobility hubs emerge from literature not as a guaranteed solution, but as a potentially important enabling infrastructure that may mitigate life cycle and operational inefficiencies when appropriately designed and contextually deployed.

Rather than demonstrating that mobility hubs inherently reduce CO_2 emissions, this review clarifies the conditions under which hubs are most likely to contribute positively to urban decarbonization—specifically when they support high rates of private car substitution, reduce indirect emissions from rebalancing and maintenance, and operate within low-carbon electricity systems. Recognizing these conditions is essential for translating the theoretical potential of emerging mobility systems into sustained, system-wide emission reductions.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

FT: Writing – review & editing, Writing – original draft, Conceptualization, Investigation, Visualization. EK: Investigation, Conceptualization, Supervision, Writing – review & editing, Methodology. NO: Supervision, Writing – review & editing. AB: Supervision, Writing – review & editing. SH: Supervision, Writing – review & editing.

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Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/frsc.2026.1685930/full#supplementary-material

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